NOνA

NuMI Off-axis ν_e Appearance Experiment

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For the NOvA Collaboration

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"Neutrino Telescopes"

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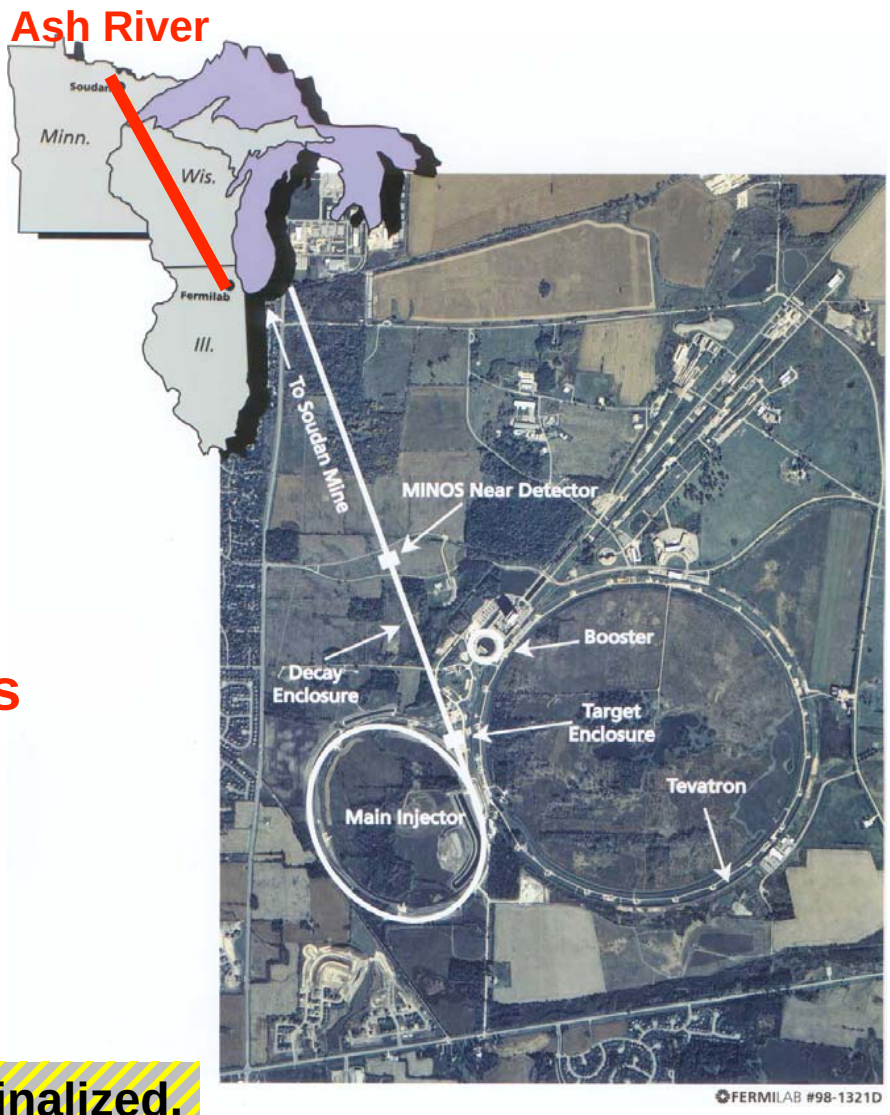
Venice

Outline

- NOνA physics
  - $\nu_\mu \rightarrow \nu_e$
  - mass hierarchy
  - CP violation
  - $\nu_\mu \rightarrow \nu_\mu$
- Experimental strategy
- Accelerator & Beam
  - current status
  - future upgrades
- Far and Near NOvA detectors
  - technology
  - update on R&D
- Summary & Outlook



NuMI at
Fermilab and Minnesota

Technical Design Report (TDR) being finalized.
All plots will be soon updated.

Sub-dominant mixing & CP-violating phase

Pontecorvo – Maki – Nakagawa - Sakata (PMNS) matrix

$$|\nu_\ell\rangle = \sum U_{\ell m} |\nu_m\rangle$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric $\nu_\mu \rightarrow \nu_\tau$

Atmospheric $\nu_e \rightarrow \nu_\mu, \nu_\tau$

Solar

$c_{ij} = \sin\theta_{ij}$

$s_{ij} = \cos\theta_{ij}$

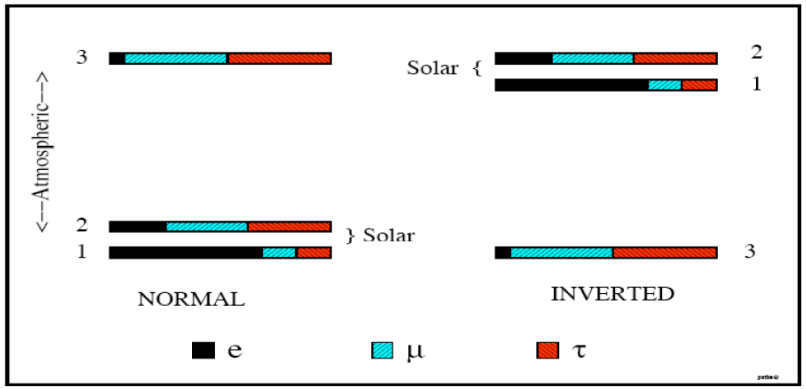
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Mass hierarchy via oscillations in matter

- In matter at oscillation maximum

$$P_{matter}(\nu_\mu \rightarrow \nu_e) = \left(1 \pm 2\frac{E}{E_R}\right) P_{vacuum}(\nu_\mu \rightarrow \nu_e)$$

- + for neutrinos with normal mass hierarchy and anti-neutrinos with inverted mass hierarchy
- – vice versa
- About a +/- 30% for NuMI to Ash River



$$P_{vacuum}(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \Delta_{atm} = 2.5\% \left(\frac{\sin^2 2\theta_{13}}{0.05}\right)$$

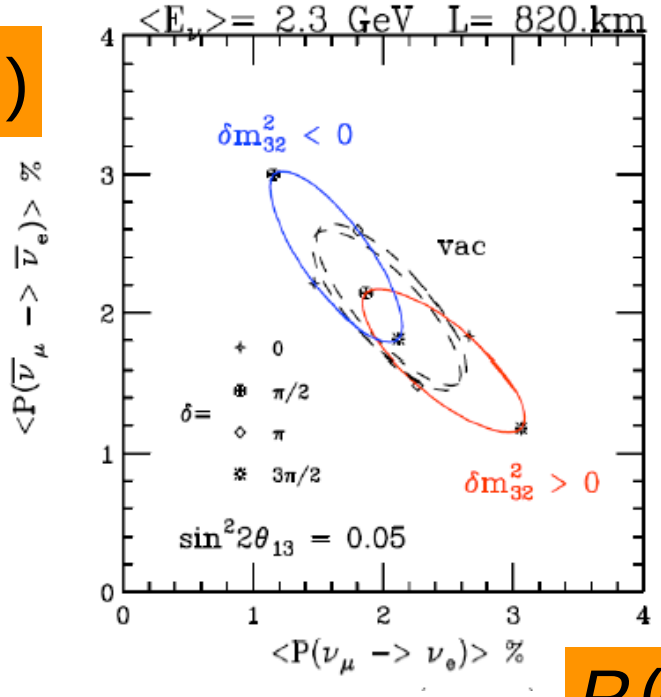
$$E_R = \frac{\Delta m^2_{32}}{2\sqrt{2} G_F N_e} \approx 11 GeV$$

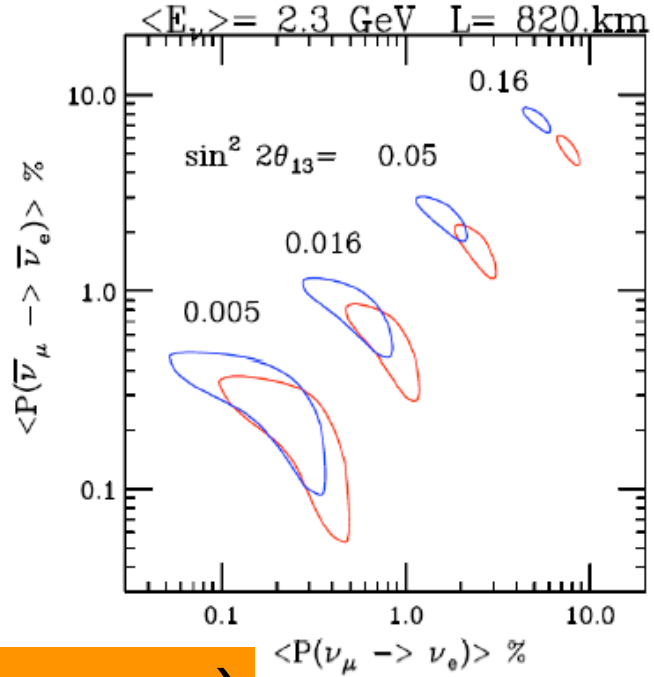
$$E_{1st\,\max} = 1.64 GeV \left(\frac{\Delta m^2_{32}}{2.5\times10^{-3} eV^2}\right)\left(\frac{L}{810 km}\right)$$

$$\Delta_{atm} \approx 1.27 \left(\frac{\Delta m^2_{32}(eV^2) L(km)}{E(GeV)}\right)$$

$\sin^2 2\theta_{13}$ versus mass hierarchy

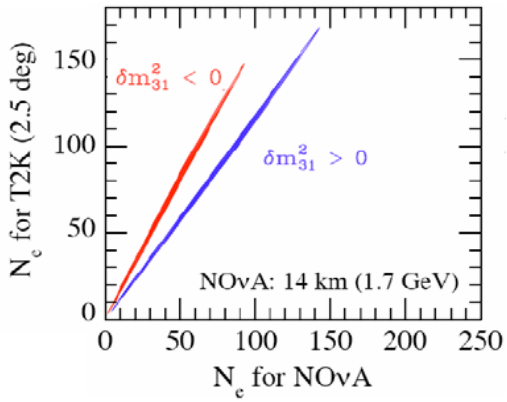
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$





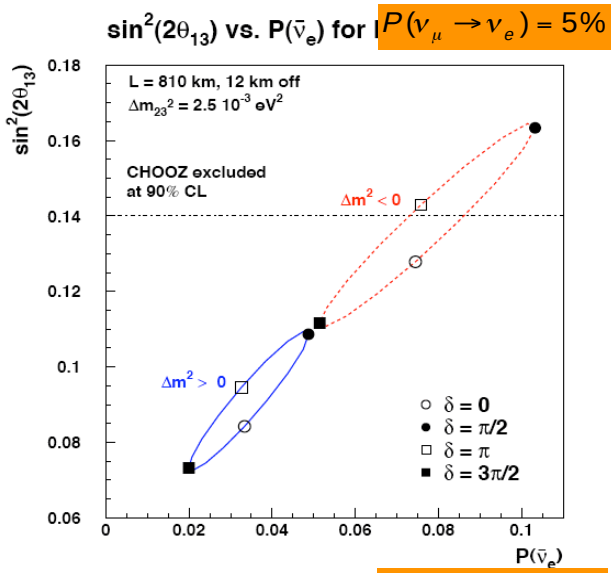
$P(\nu_\mu \rightarrow \nu_e)$

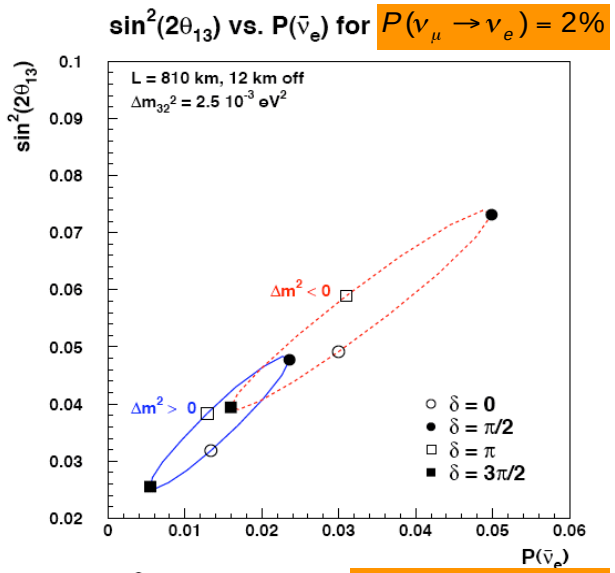
- Ambiguities
- Other measurements helpful (e.g., T2K)

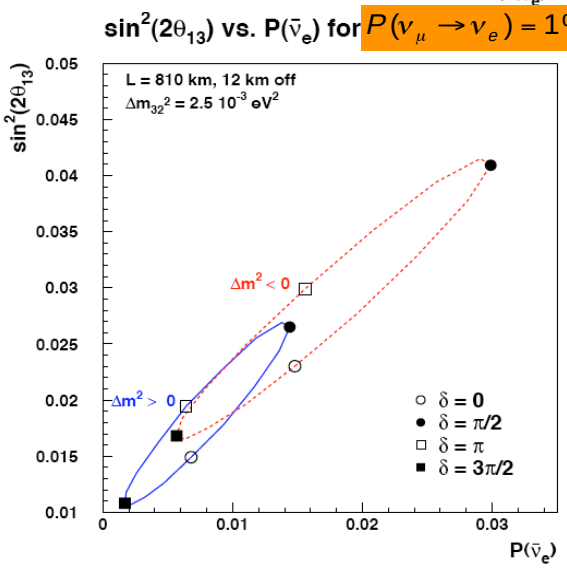


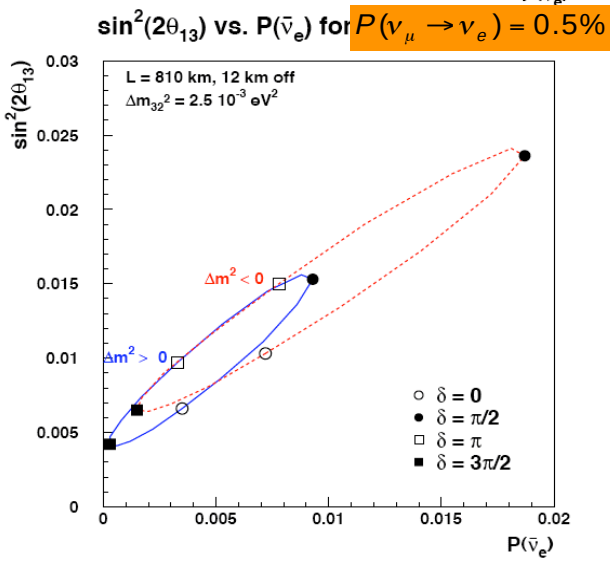
Ambiguities versus $P(\nu_\mu \rightarrow \nu_e)$

$\sin^2(2\theta_{13})$



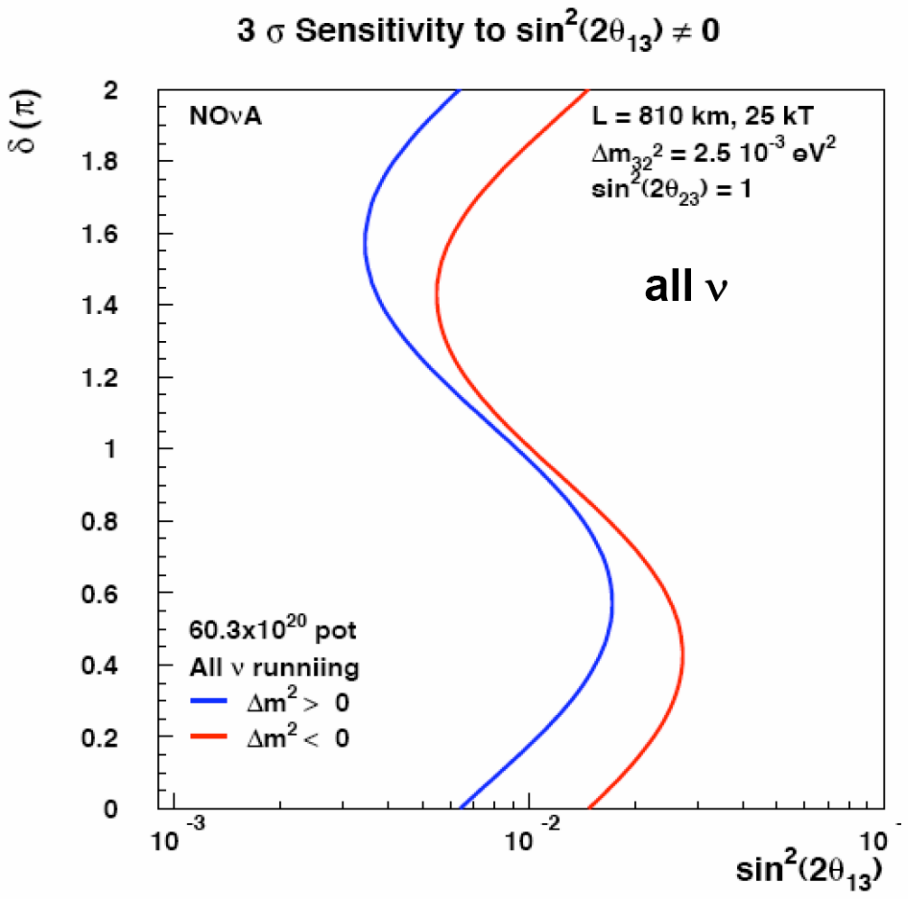


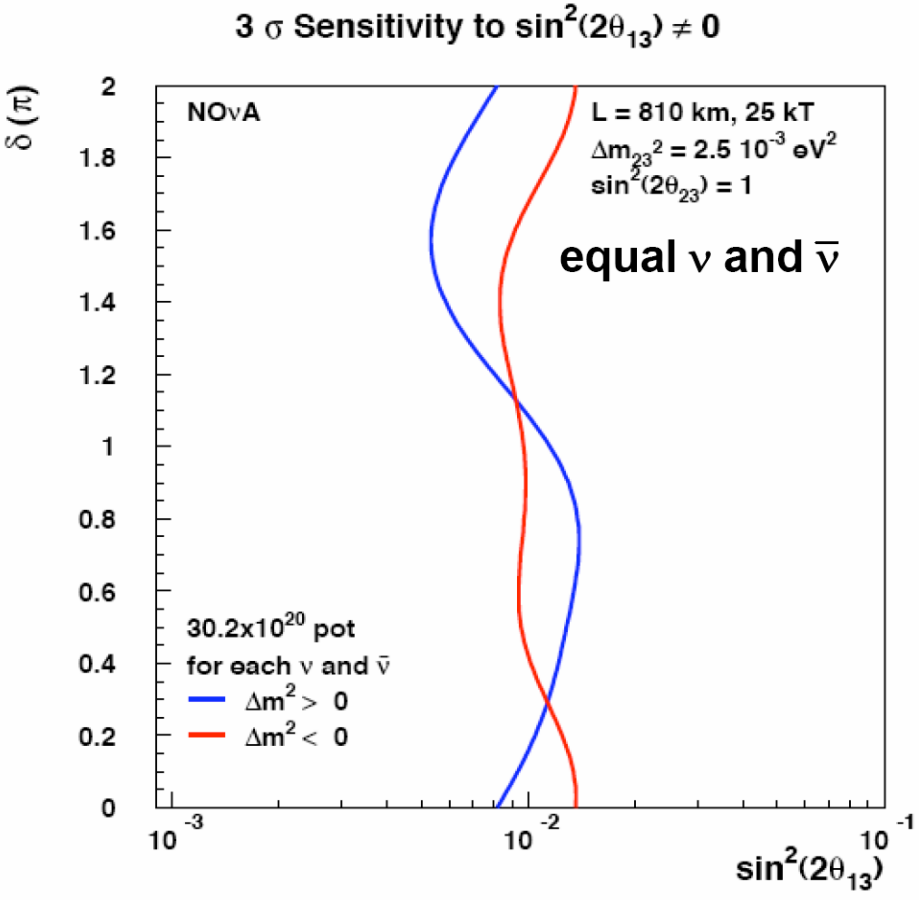




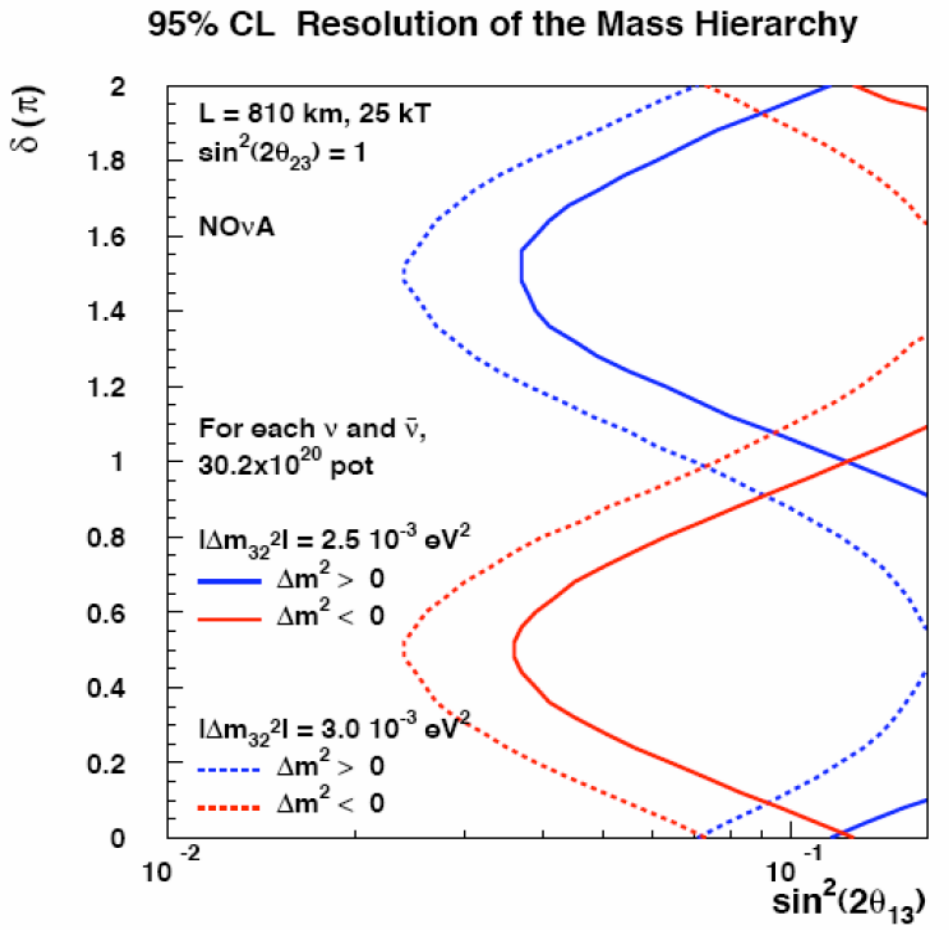
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

3 σ Sensitivity to $\theta_{13} \neq 0$



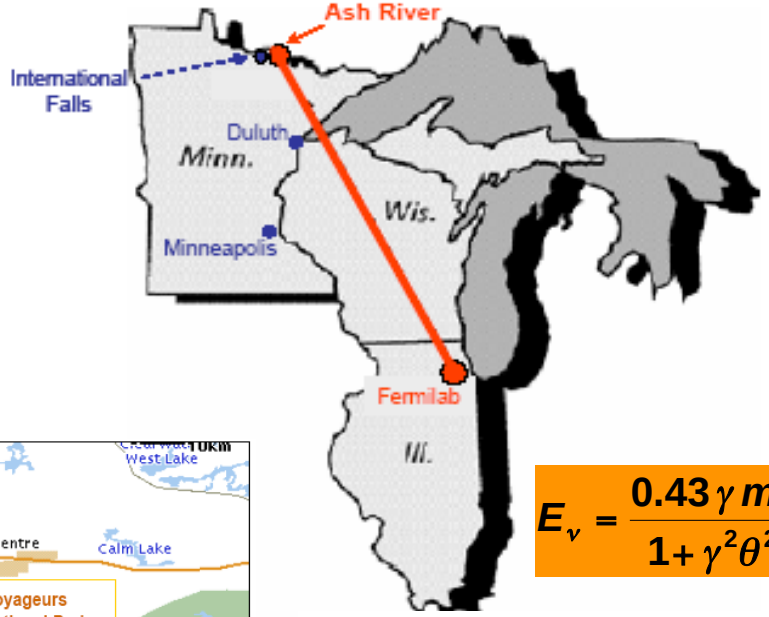


Resolution of the mass hierarchy

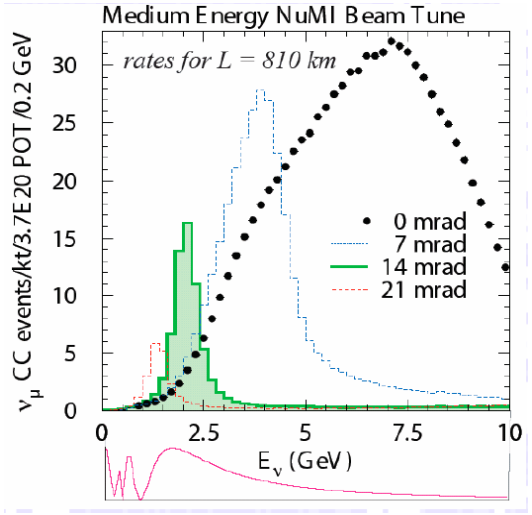


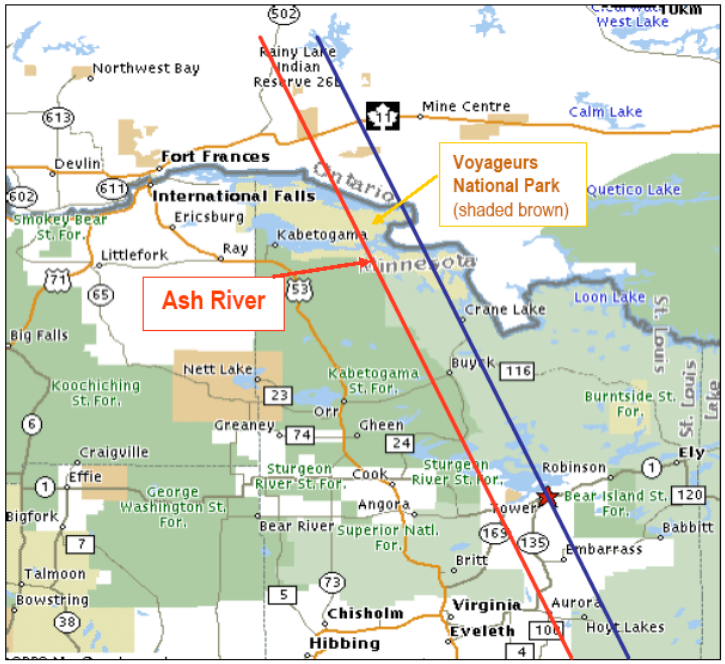
The strategy: off-axis NuMI beam

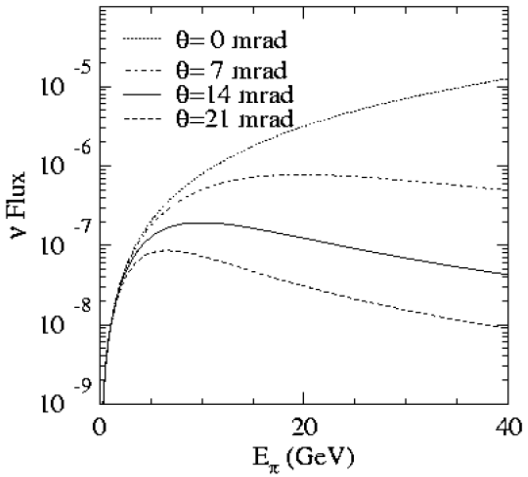
- Fermilab – Ash River
- 14 mrad off-axis
- 810 km baseline

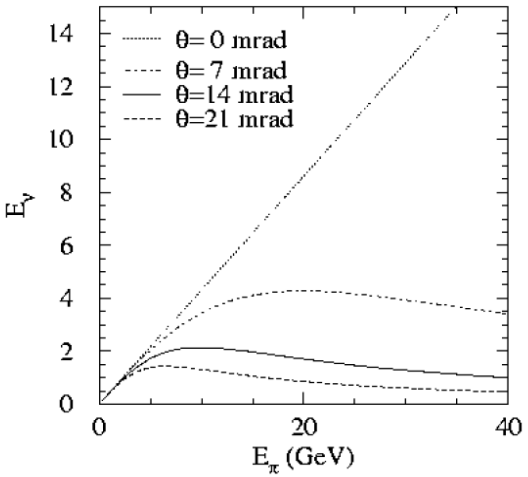


$$E_\nu = \frac{0.43\,\gamma\, m_\pi}{1+\gamma^2\theta^2}$$









Experimental setup: the Main Injector now

(Main Injector = MI)

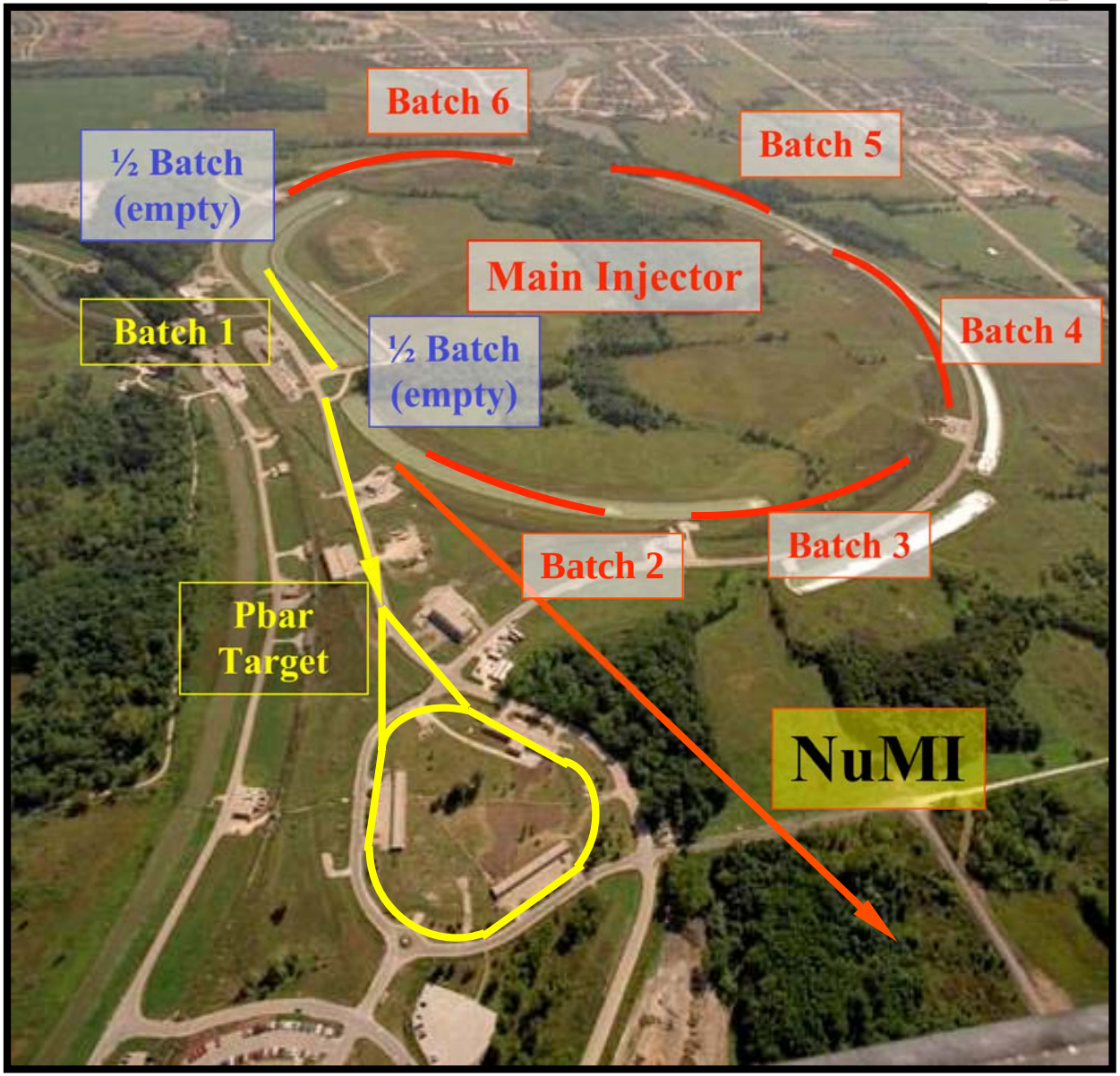
- MI is fed 1.56 μs batches from 8 GeV Booster

  (MI ramp time ~1.5sec)

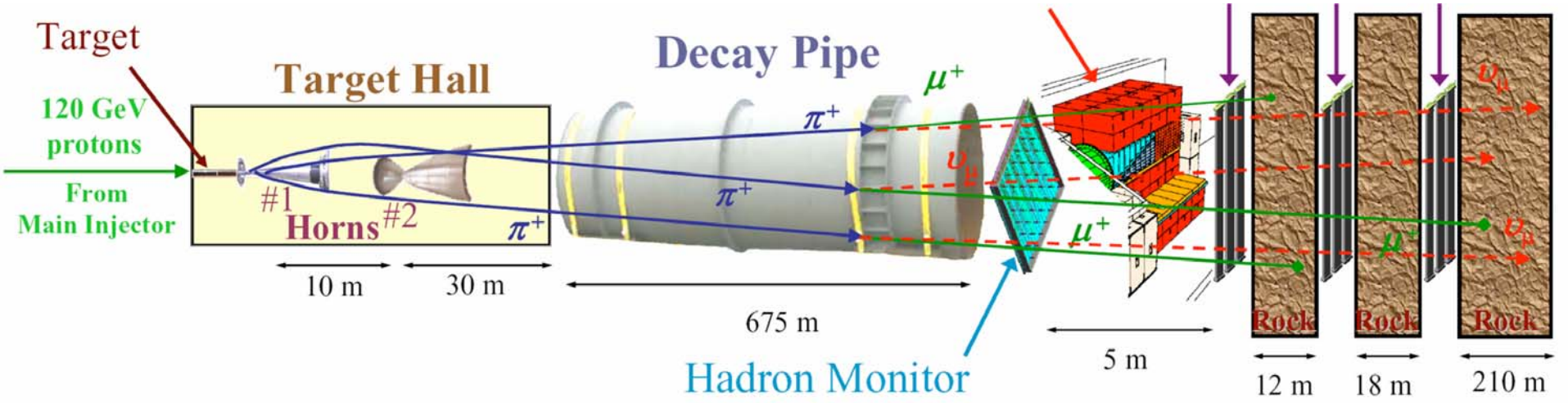
- **NuMI designed for**
  - 9.6 μsec single turn extraction
  - 4×10^{13}ppp @ 120 GeV
  - 1.9 second cycle time
  - beam power 400kW

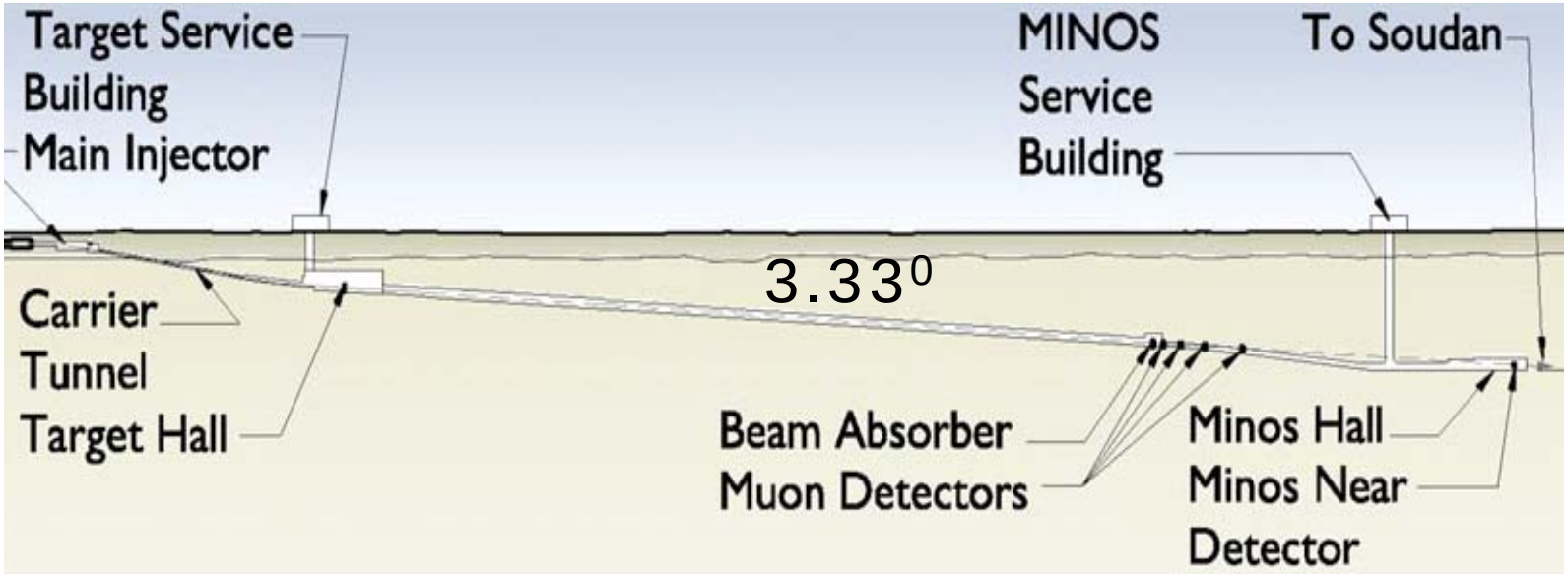
- **Typical performance to date:**
  - 2.4×10^{13} ppp @ 120 GeV
  - 2.2-2.4 second cycle time

- **Achieved records:**
  - 4.05×10^{13} ppp @ 120 GeV (Feb 22, 2007)
  - 2.0 second cycle time
  - 315 kW

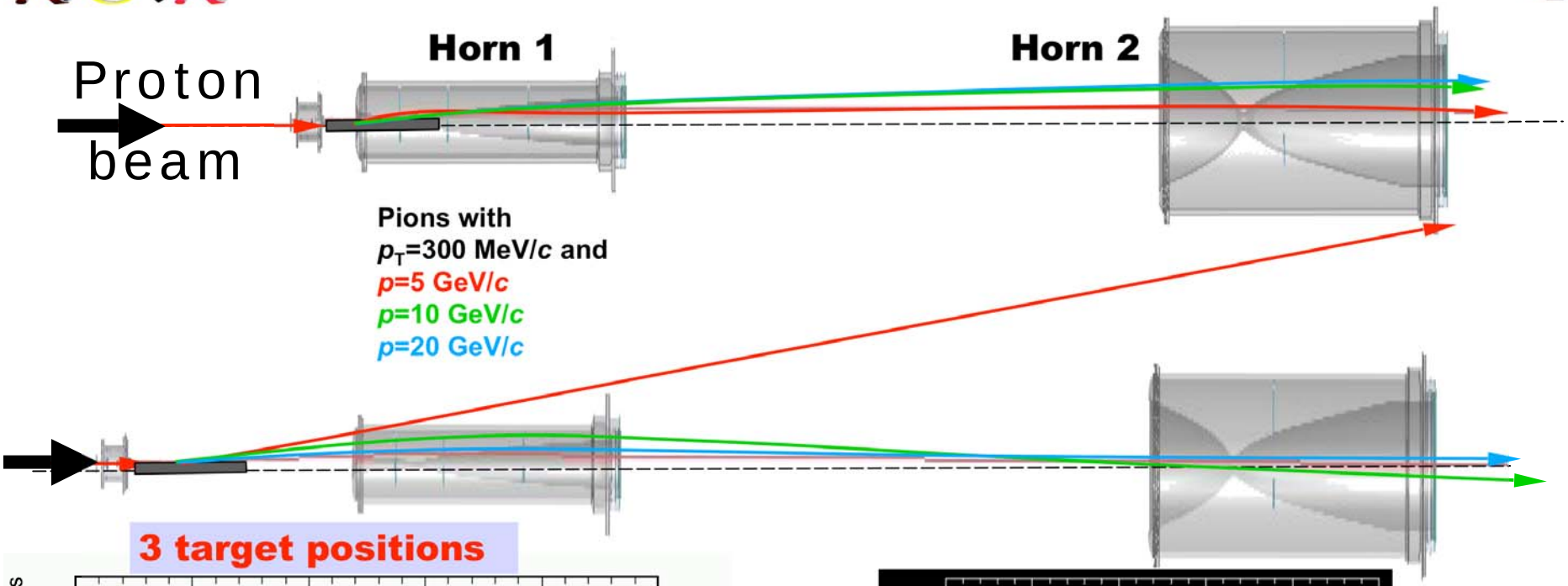


Experimental setup: NuMI beam

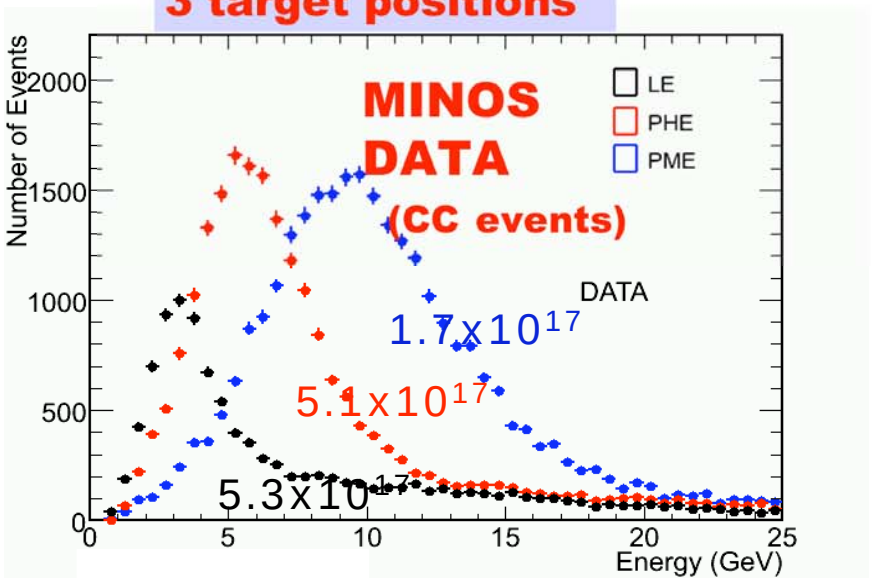


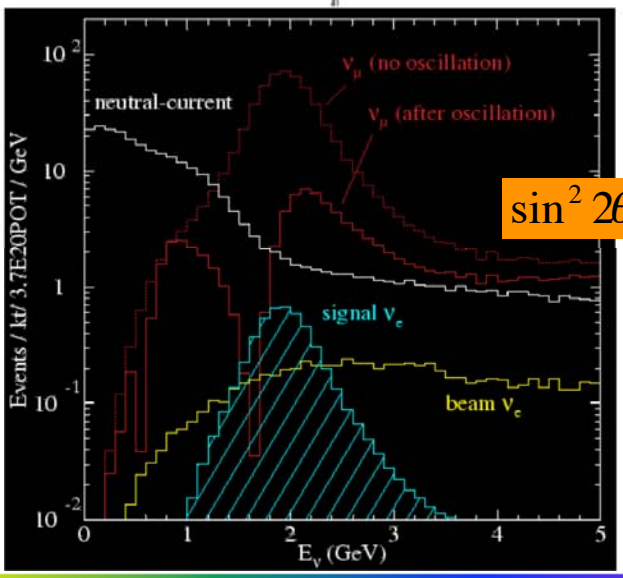


NuMI – multi-beam



3 target positions





$\sin^2 2\theta_{13} = 0.04$

Proton Improvement Plan

❑ More protons with Collider (<2009)

- 9/11 slip-stacked Booster Batches (2 batches for anti-protons)
- Repetition rate = 0.8 s (Booster) + 1.4 s (MI ramp) = 2.2 s
- 3.4 x 10^{20} protons/year

❑ Post-Collider era w/ Recycler (2010-2011)

(Accelerator and NUmI Upgrade [ANU])

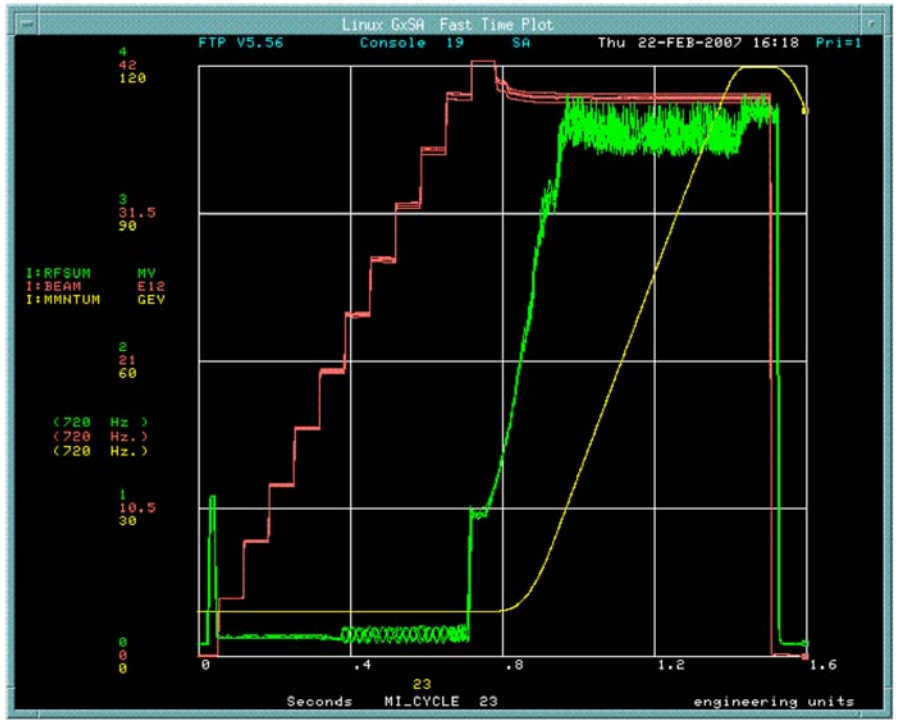
- 12 batches
- use Recycler for slip stacking (1.33 s cycle)
- 6 x 10^{20} protons/year

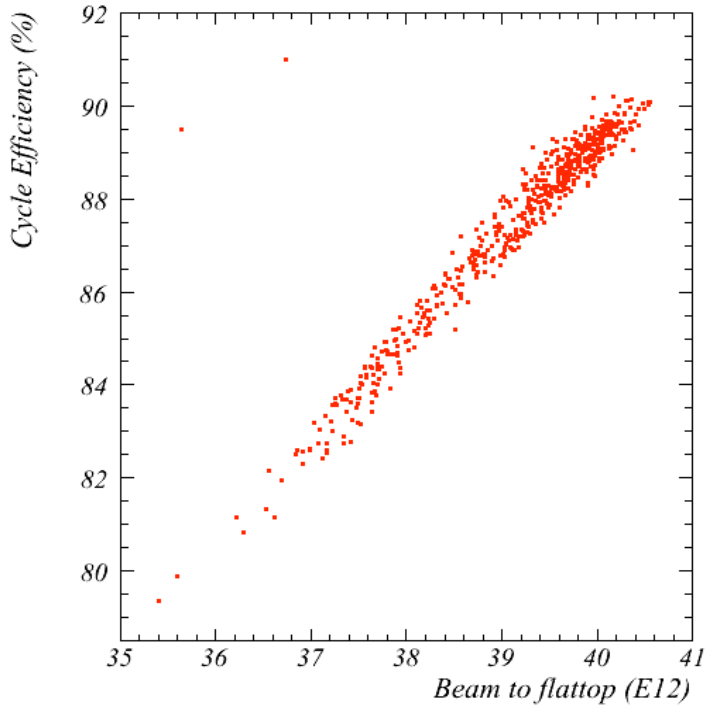
❑ Post-Collider era w/ Accumulator (>2012)

- Use Accumulator (for momentum stacking)
- 10 x 10^{20} protons/year

Very recent progress

- 4.05×10^{13} ppp slip-stacked in 11 batches **(on Feb 22, 2007)**





Operating Scenarios

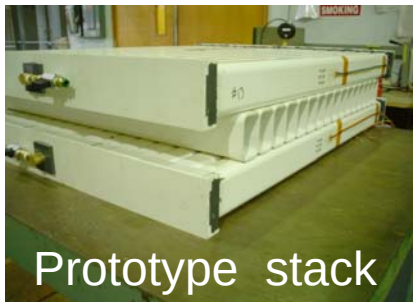
	Present operating conditions *	Proton Plan Multi-batch slip-stacking in MI *	NOvA ANU Multi-batch slip-stacking in Recycler	Proposed SNuMI Accumulator momentum stacking
Booster intensity (p/batch)	4.5_10^{12}	4.3_10^{12}	4.3_10^{12}	4.7_10^{12}
No. Booster batches to NuMI	5	9	12	18
MI cycle time (s)	2	2.2	1.333	1.333
MI intensity (ppp)	3.1_10^{13}	4.5_10^{13}	4.9_10^{13}	8.3_10^{13}
To NuMI (ppp)	2.25_10^{13}	3.7_10^{13}	4.9_10^{13}	8.3_10^{13}
NuMI beam power (kW)	210	320	700	1200
POT/yr to NuMI	2_10^{20}	3_10^{20}	6_10^{20}	10_10^{20}
MI protons/hr	5.5_10^{16}	7.3_10^{16}	1.3_10^{17}	2.2_10^{17}

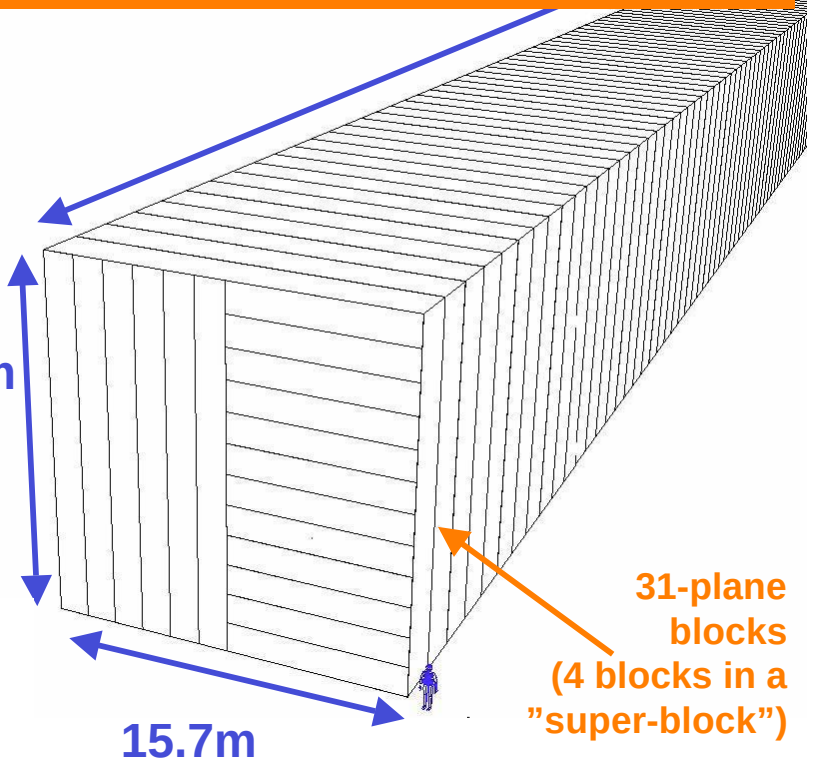
* NuMI values are given for mixed-mode cycles

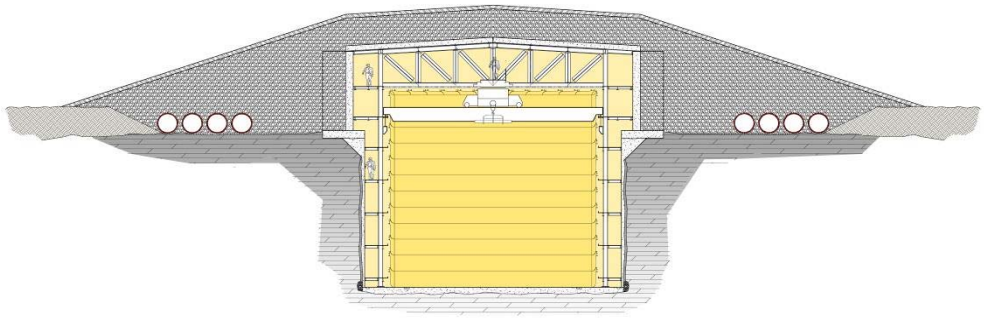
NOνA Far Detector we would like to build

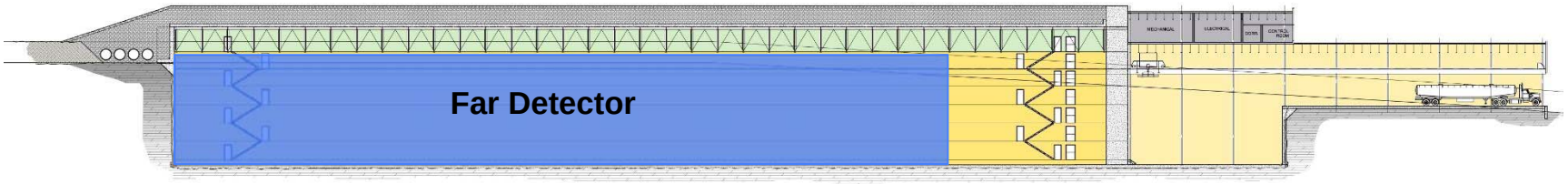
We will build as much of this as the funding will allow…

- TAD = Totally Active Detector
  PVC = passive material
- mass N kT (N large)
  ~80% scintillator
  ~20% PVC extrusions
- Modular structure
  32 cells/extrusion
  12 extrusions/plane
  1984 planes
- Cell dimensions:
  3.9 cm x 6 cm x 15.7m
- U-shaped 0.7 mm WLS fiber into APD
- X_0 = 44 cm ρ_M = 10 cm

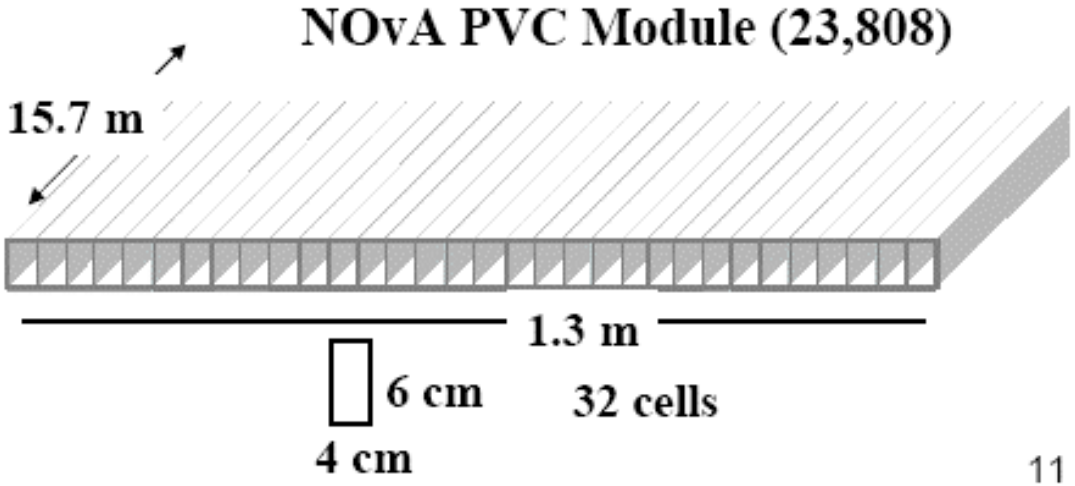








Detector technology



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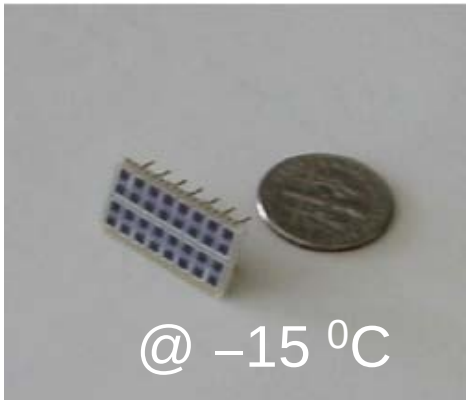
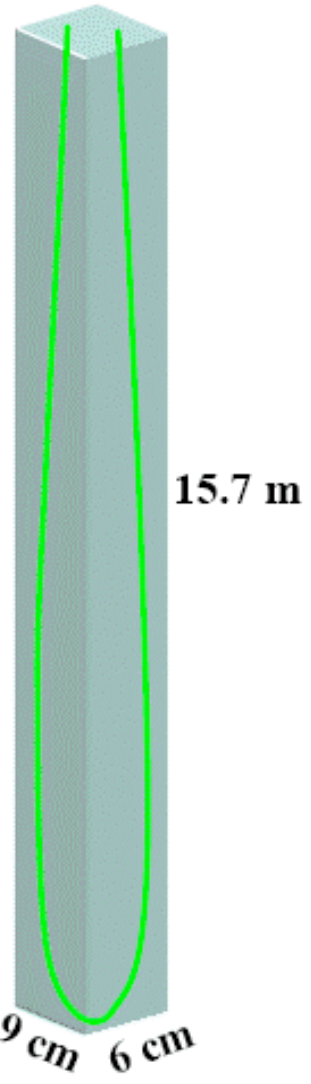
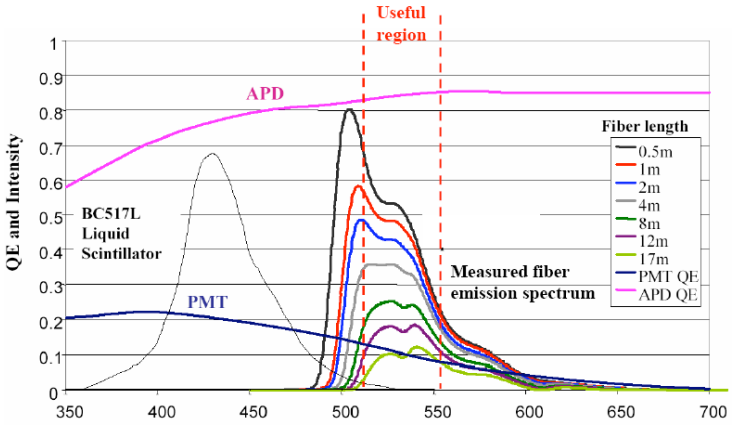




Active readout components:

- Liquid scintillator
  - filled cells.
- WLS fiber
  - 0.7 mm diameter
  - looped end ("perfect" reflector)
  - readout both ends on one side
- Avalanche Photodiode
  - Hamamatsu multi-pixel
  - 85% QE



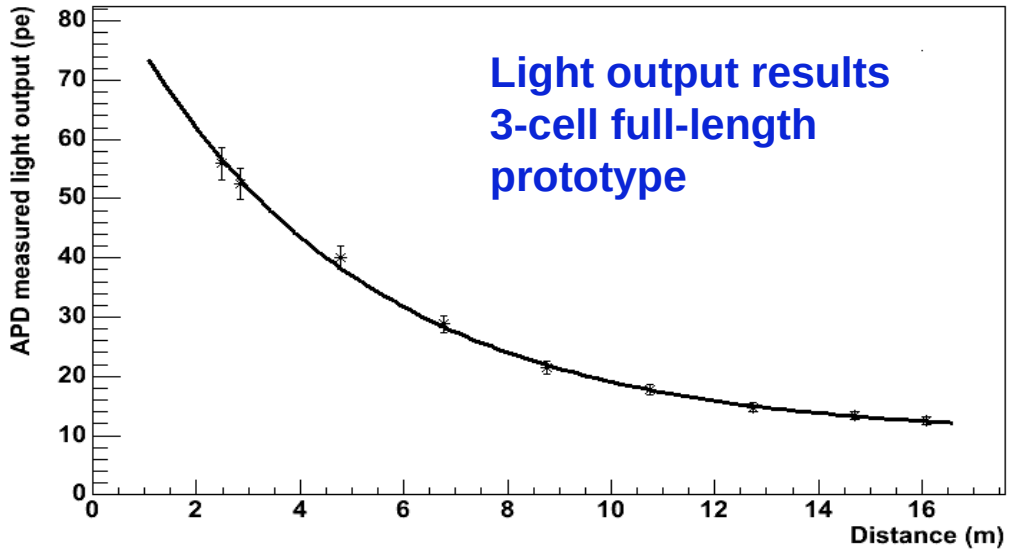
Scintillator, light yield

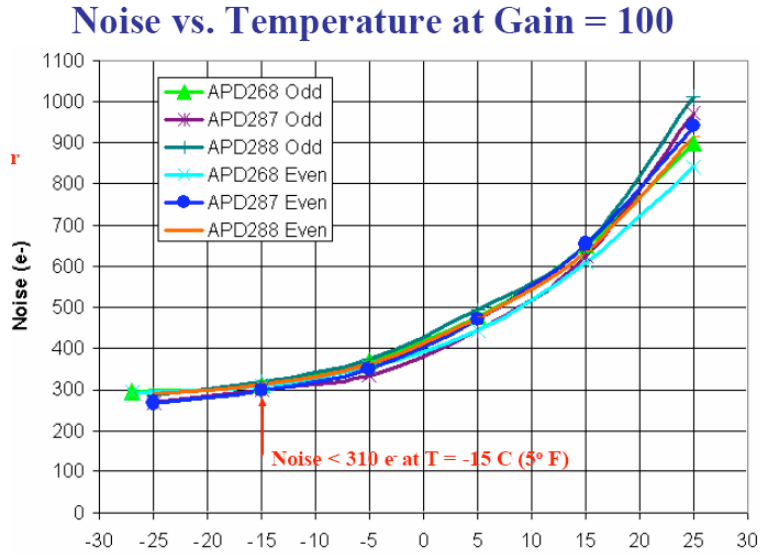
- **NOνA recipe**

  Equivalent to Saint-Gobain (Bicron) BC-517P or Eljen Technology EJ-321P

- **Requirement: 20PE's for a MIP at far extrusion-end**

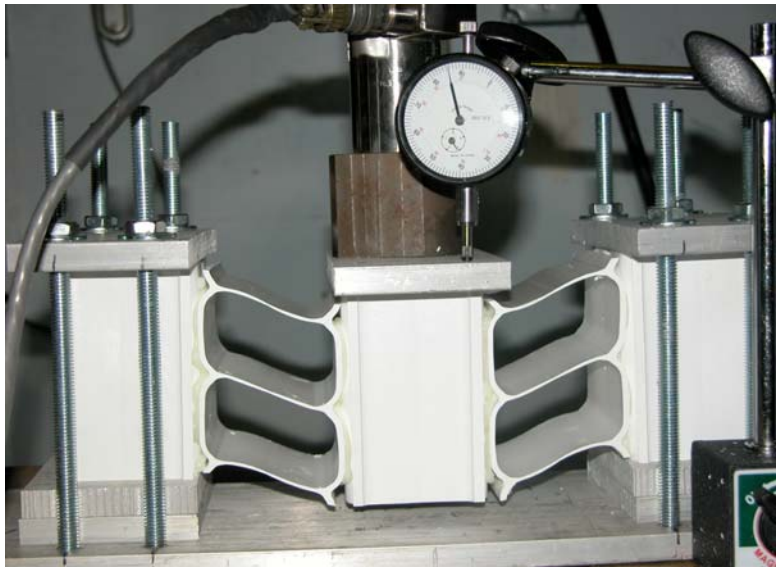
Component	Purpose	Mass fraction
mineral oil	solvent	94.4%
pseudocumene	scintillant	5.5%
PPO	waveshifter #1	0.1%
bis-MSB	waveshifter #2	0.002%
Stadis-425	anti-static agent	0.0003%
tocopherol	anti-oxidant	0.0010%
TOTAL		100%



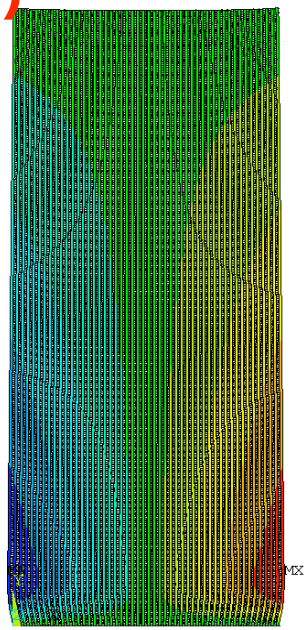


Structural challenges

❑ FEA calculations and tests (on-going)



31-plane block



ANSYS 11.0BETA
OCT 30 2006
11:00:25
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
UX (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.47318
SMN =-.079761
SMX =.079761
-.079761
-.062036
-.044312
-.026587
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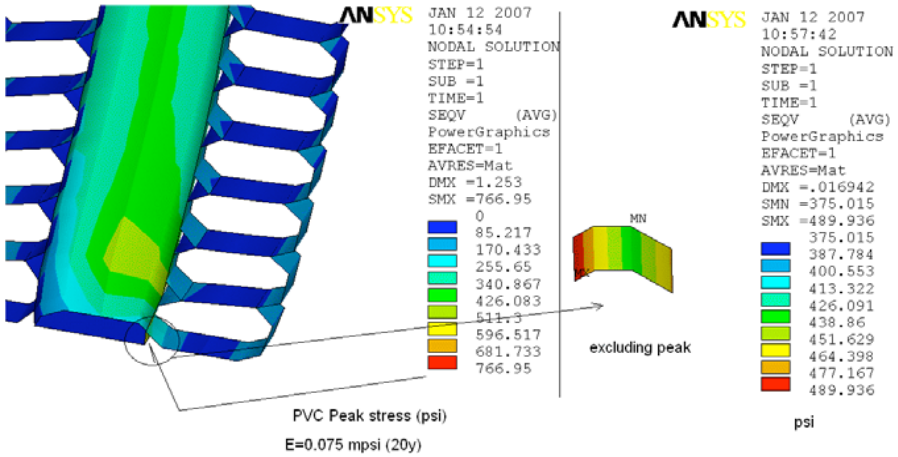
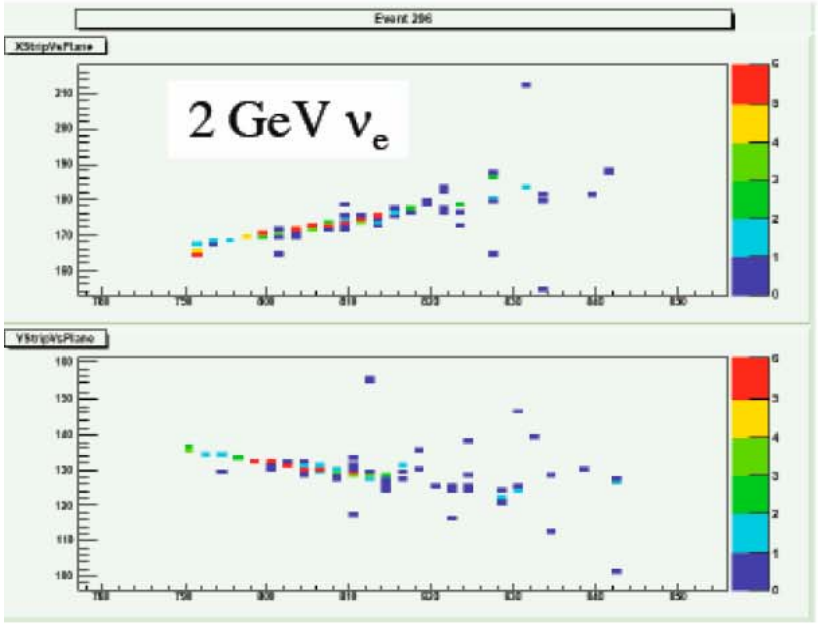
.026587
.044312
.062036
.079761
inch

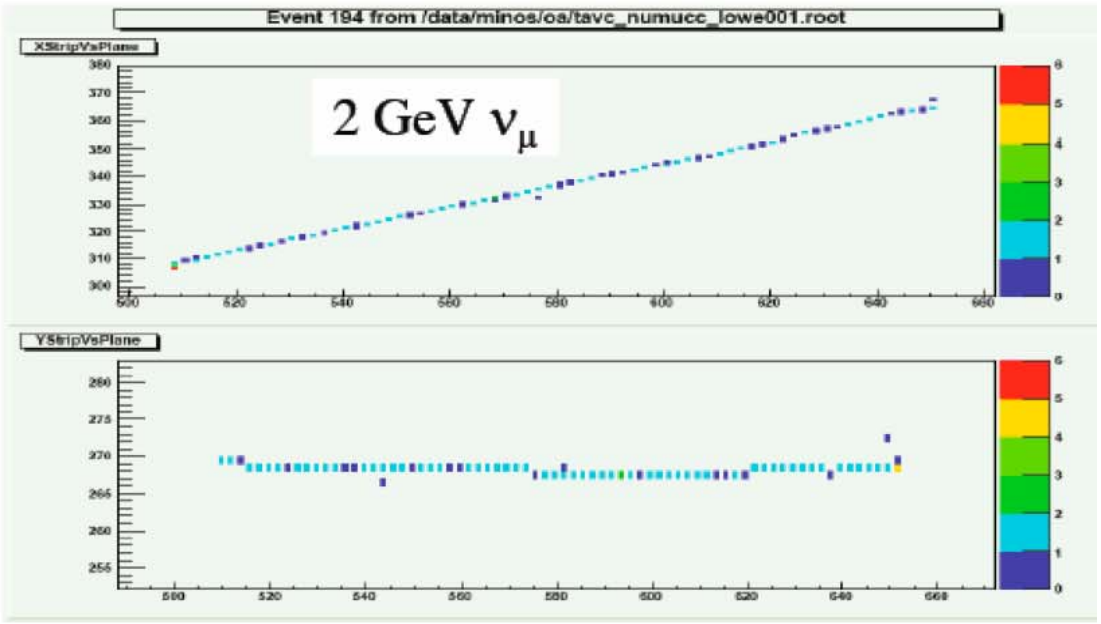
deflection for 99 planes block



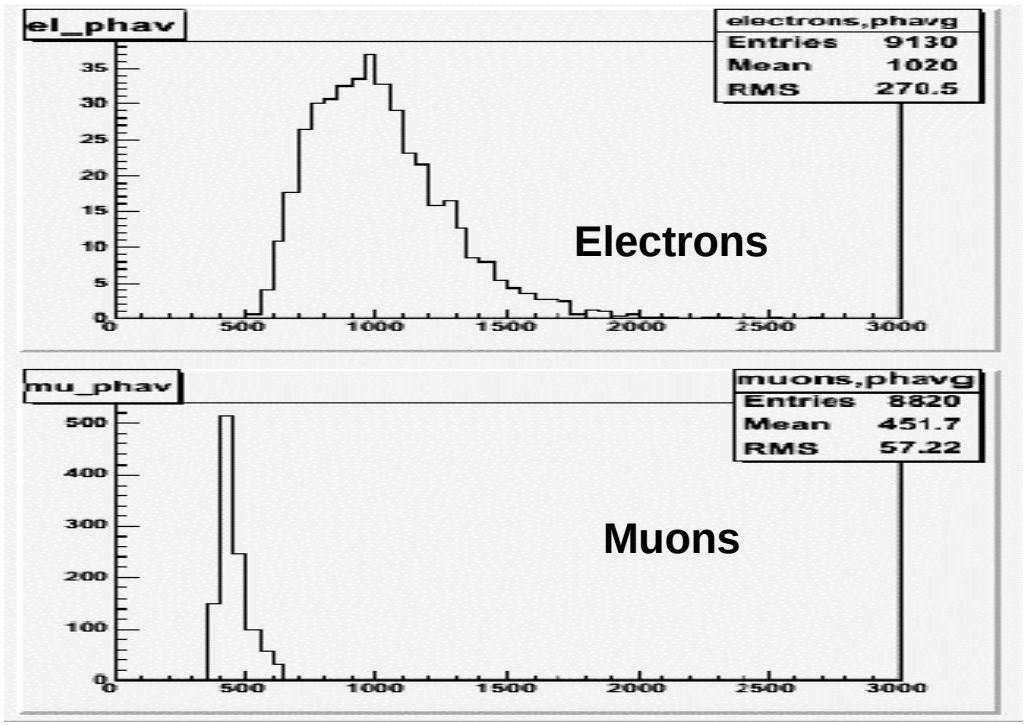
Event classification

- Longitudinal sampling every 0.15 X0
- 2 GeV muon traverses ~60 planes

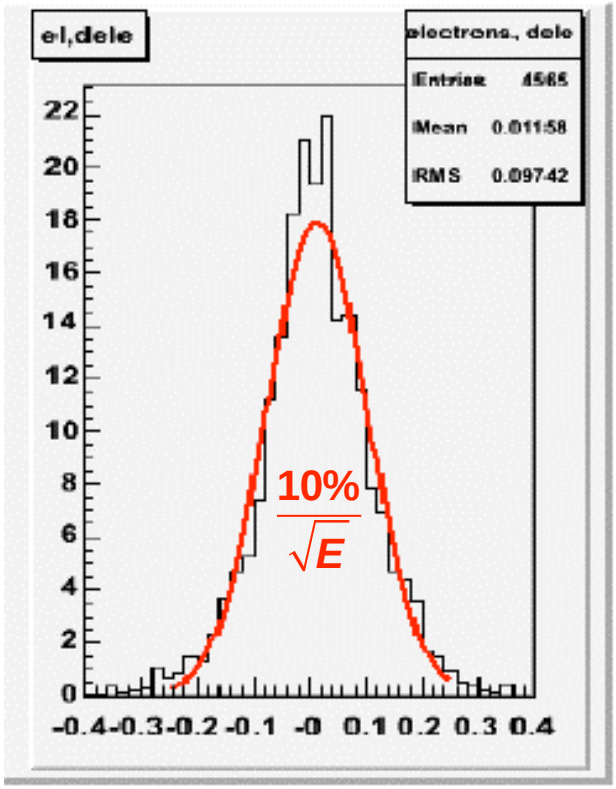




Electron ID and Resolution



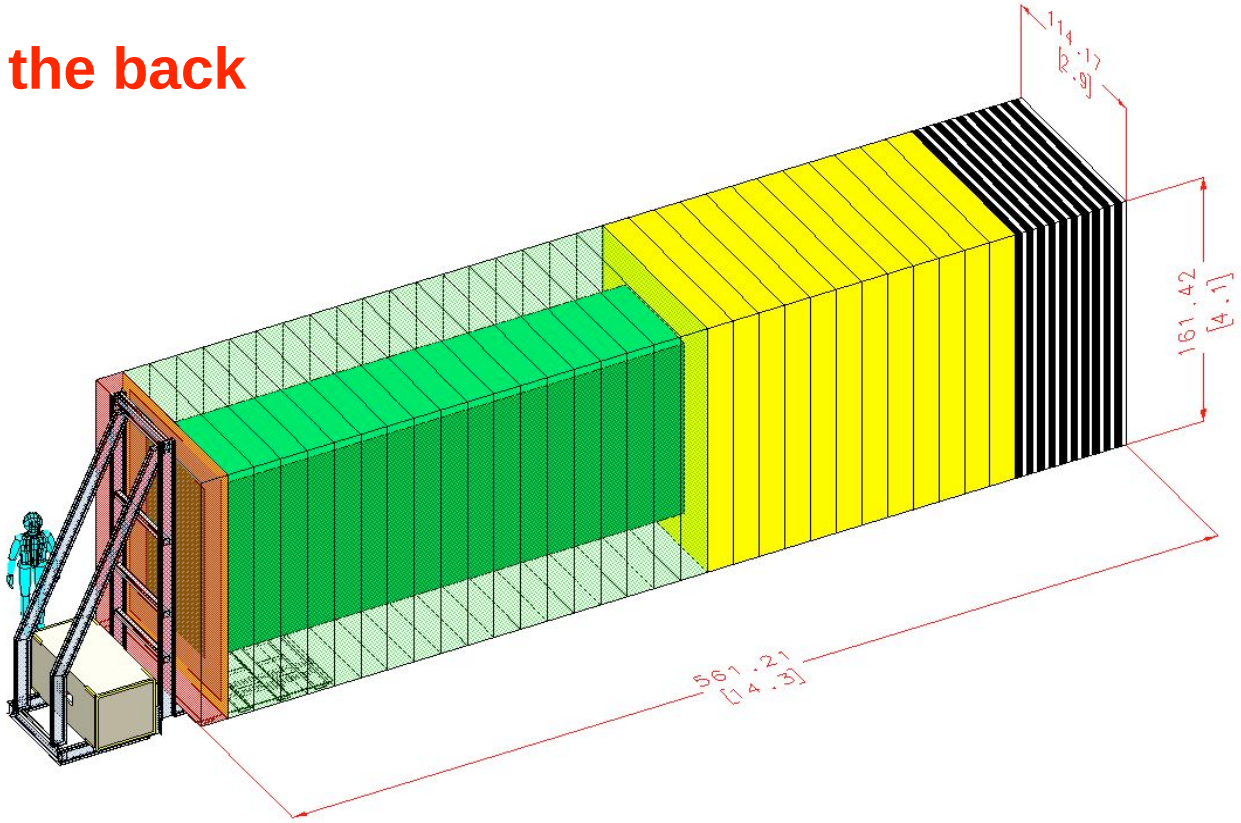
Average pulse height per plane



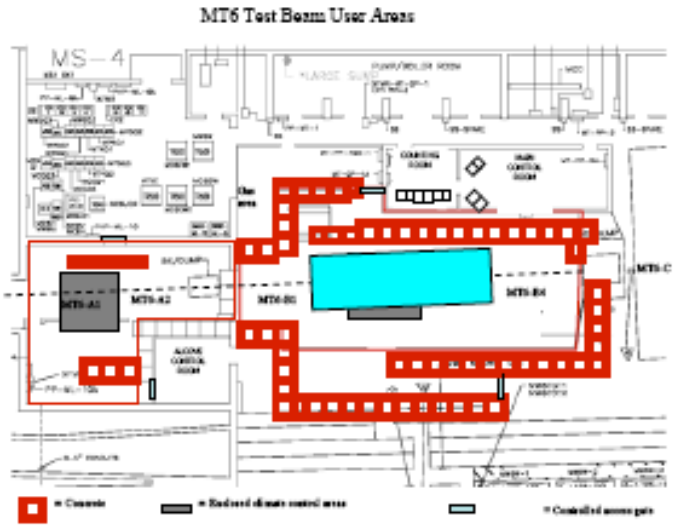
Electron energy resolution

Near Detector

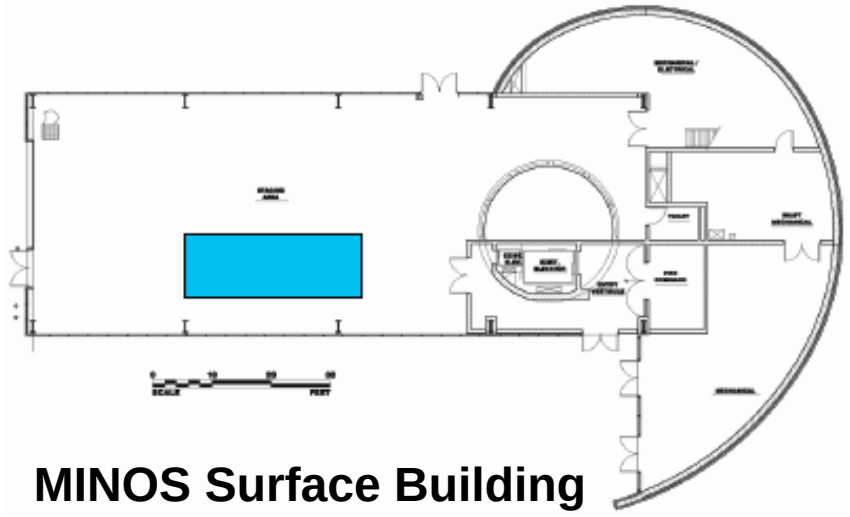
- 2000 ν_e CC events per year
- 20 tons fiducial volume
  - 1.65 x 2.85 x 7.4 m^3
- Muon catcher in the back



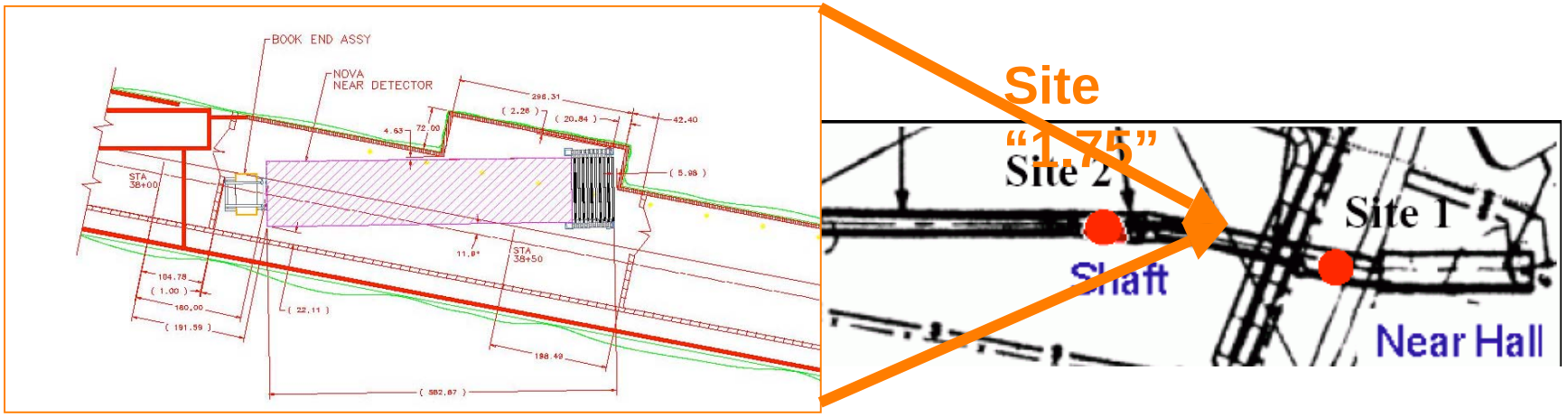
Near Detector in the beam(s)



M Test



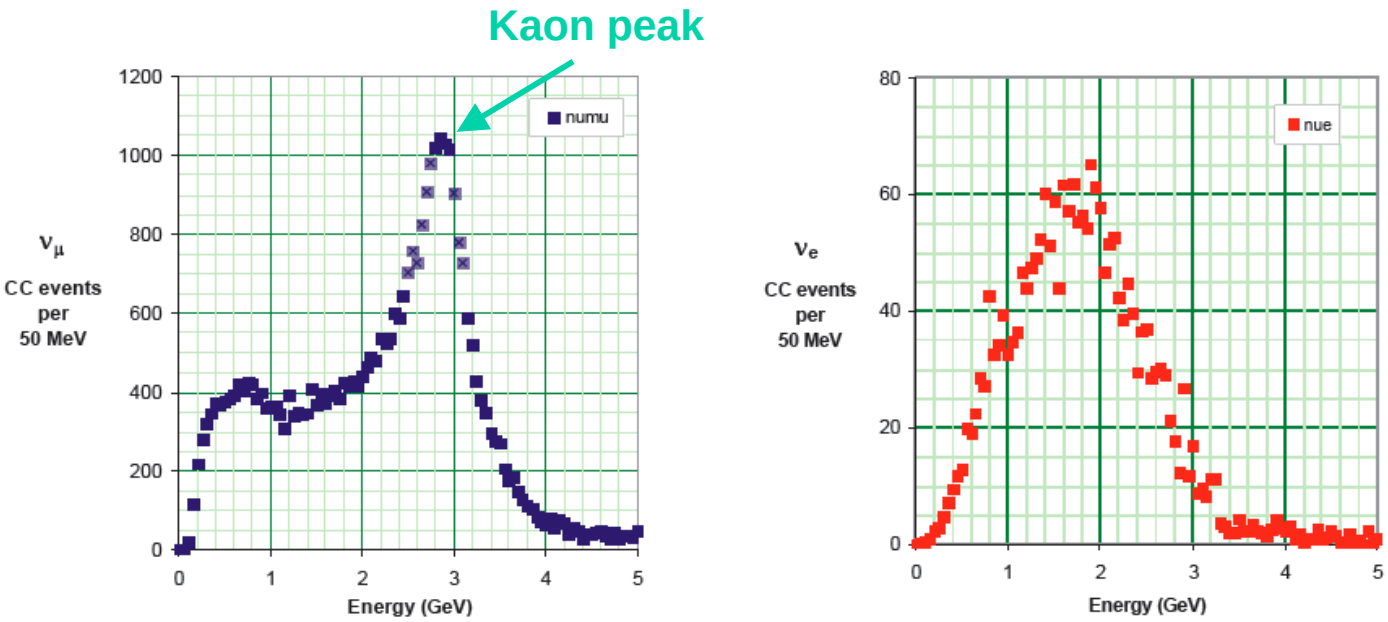
MINOS Surface Building



NuMI Access Tunnel
(100 m underground)

Near Detector in MINOS Surface Building

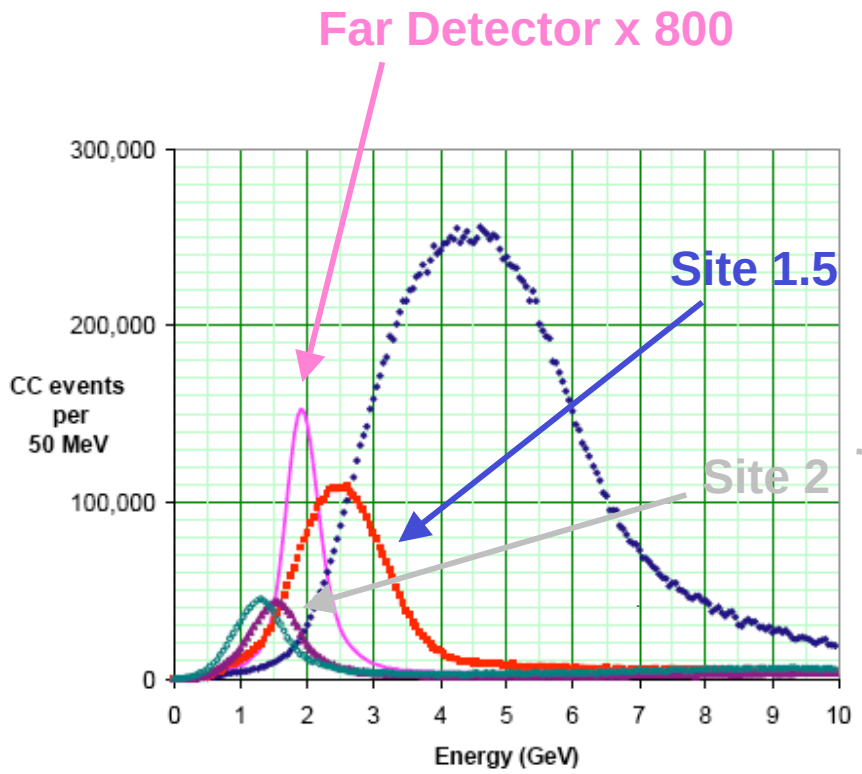
6.5 x 10^{20} pot in 75 mrad off-axis beam



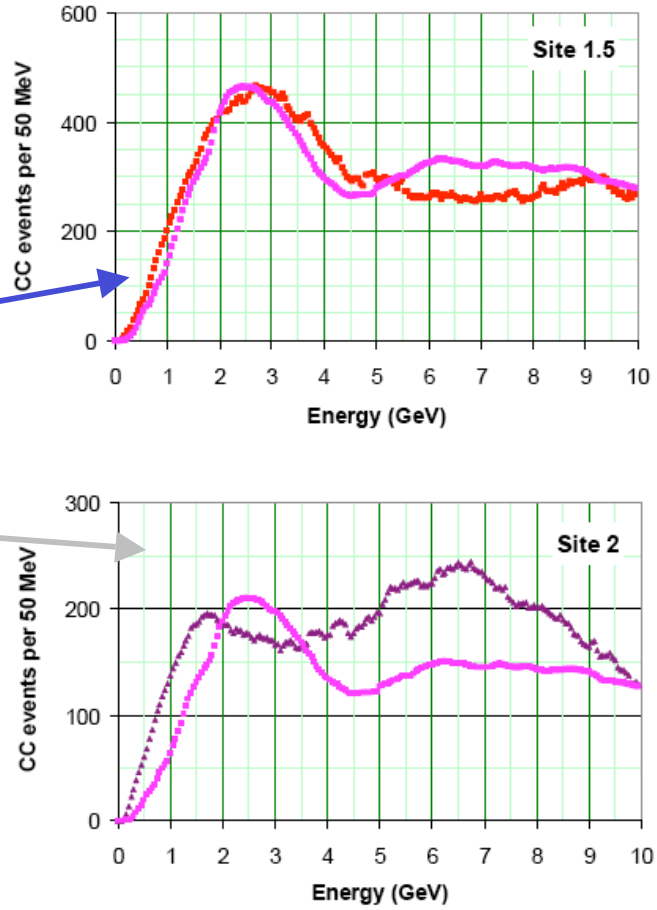
45,000 ν_μ CC events

2,200 ν_e CC events

Near Detector in the NuMI Access Tunnel



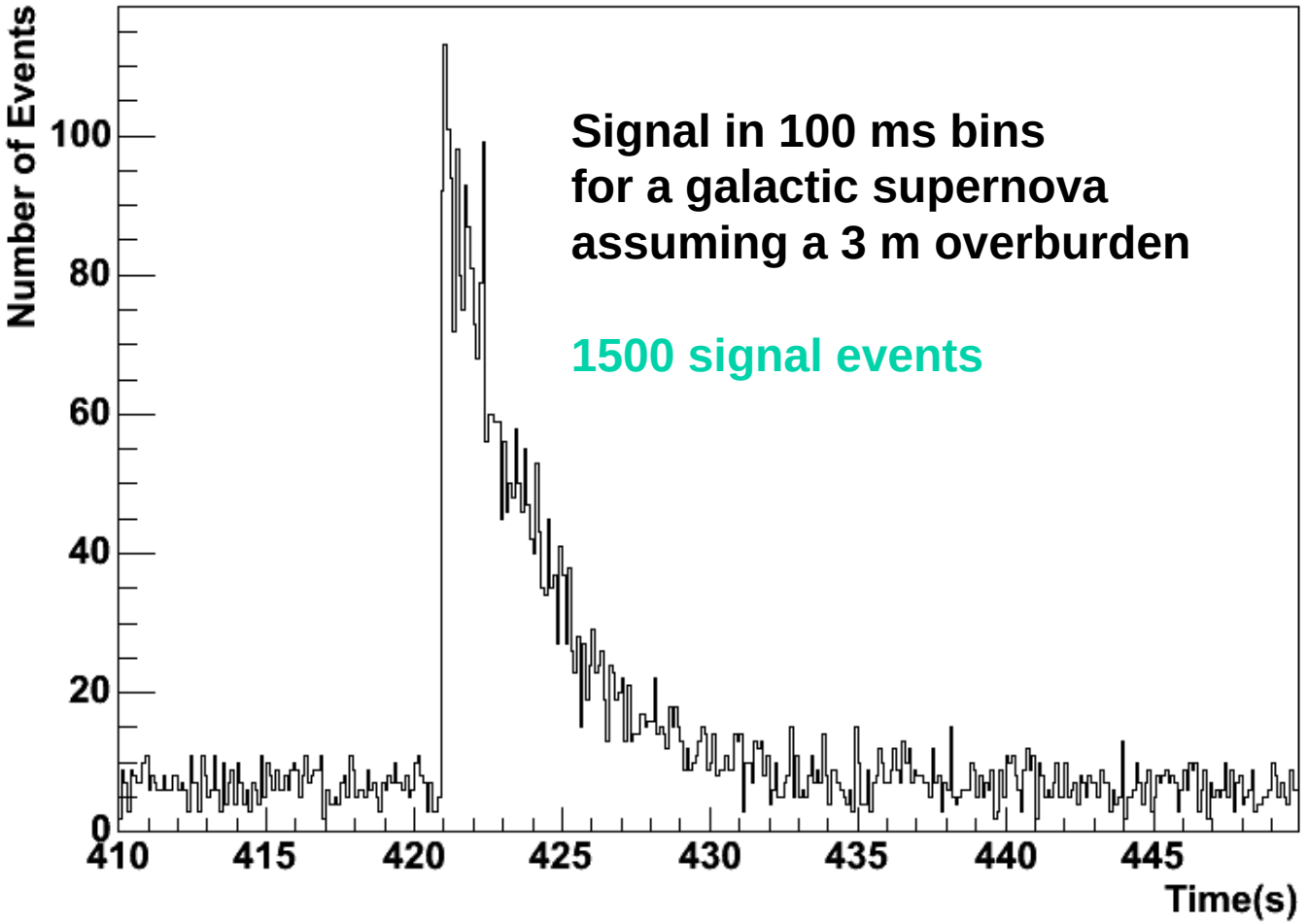
ν_μ CC events



ν_e CC events

For 6.5 10^{20} pot

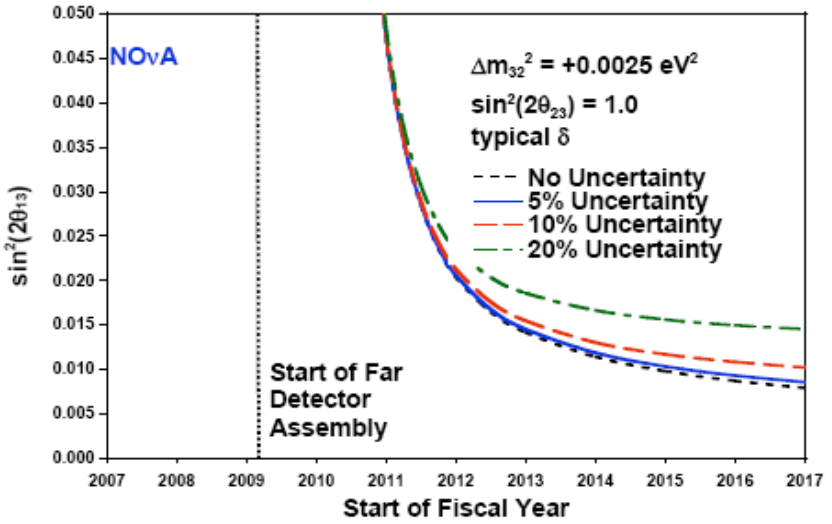
Sensitivity to a Galactic Supernova



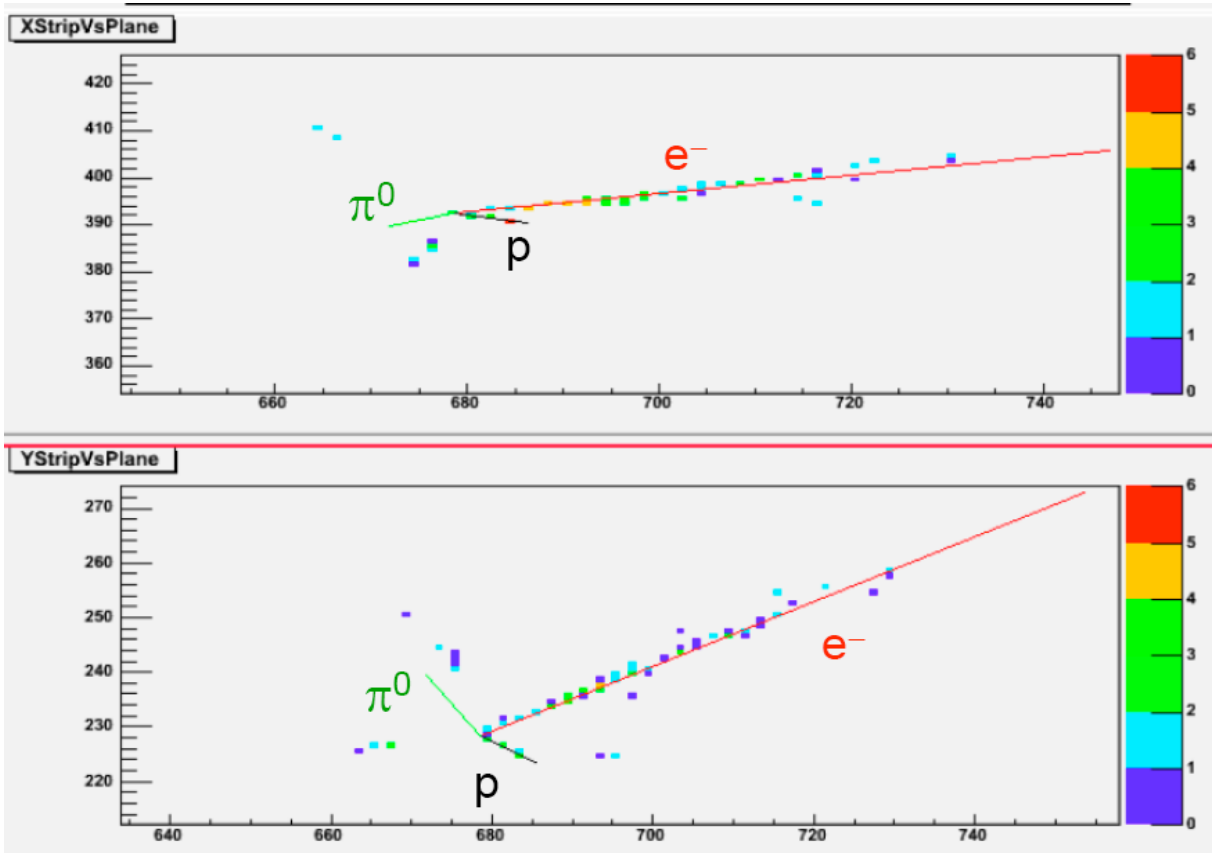
Summary and outlook

- **NOνA will address central neutrino physics issues**
  - Subdominant mixing $\sin^2(2\theta_{13})$ to about 1-2%
  - Neutrino mass hierarchy
  - CP violation (δ in PMNS matrix)
  - measure $\sin^2(2\theta_{32})$ to about 1-2%
- **Robust and straightforward detector design**
  - In-house scintillator
  - Long WLS fibers readout by APD's
  - Modular (early start of data collection)
- **Accelerator & NuMI Upgrade**
  - 700 kW by 2009
  - 1200 kW after 2012
- **Near term**
  - NOvA in FY08 budget @ $36M
  - TDR
  - prototype detector
  - testbeam

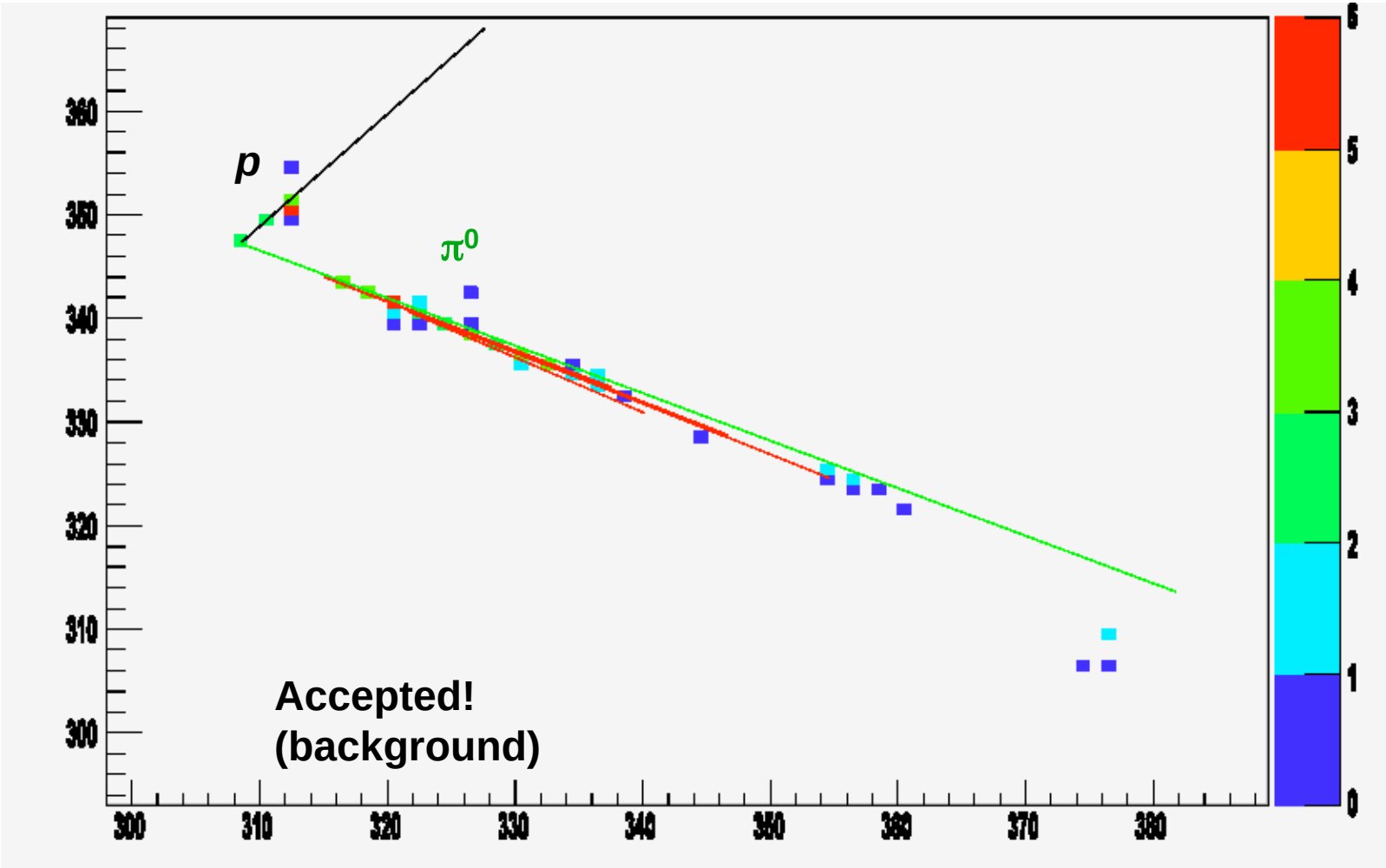
3 σ Sensitivity to $\theta_{13} \neq 0$



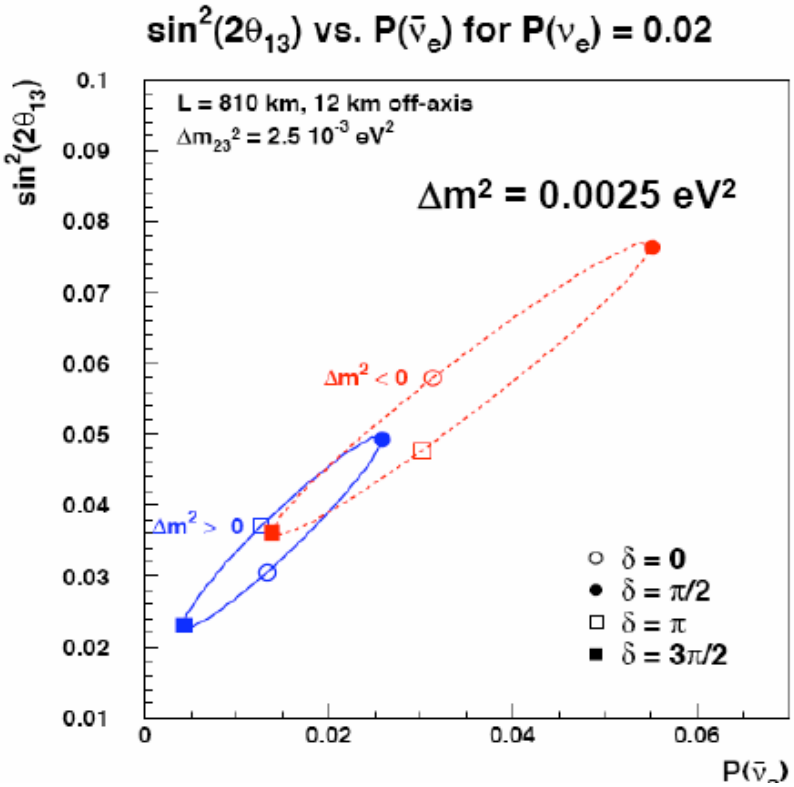
1.65 GeV $\nu_e N \rightarrow e p \pi^0$

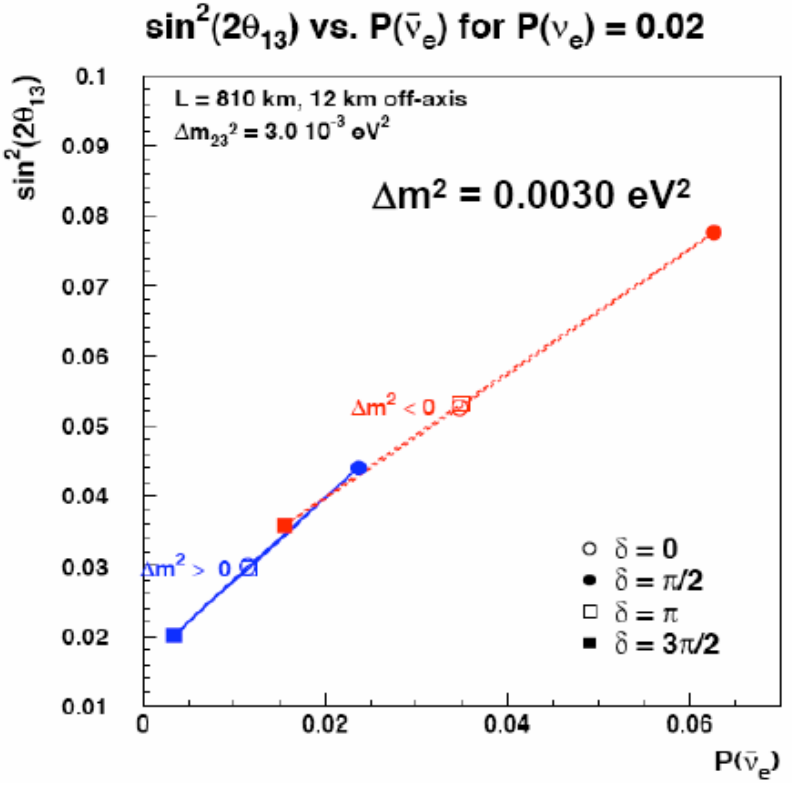


2.11 GeV $\nu_\mu N \rightarrow \nu_\mu p\pi^0$
x-z View

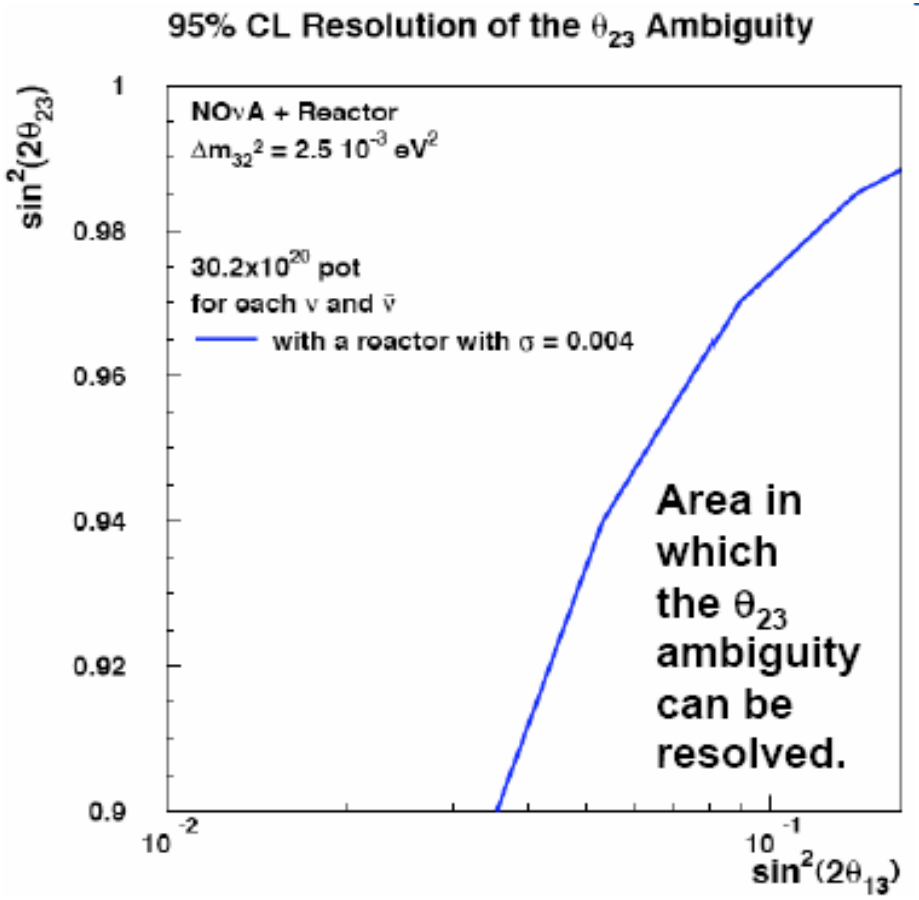


Ambiguities versus Δm^2_{23}



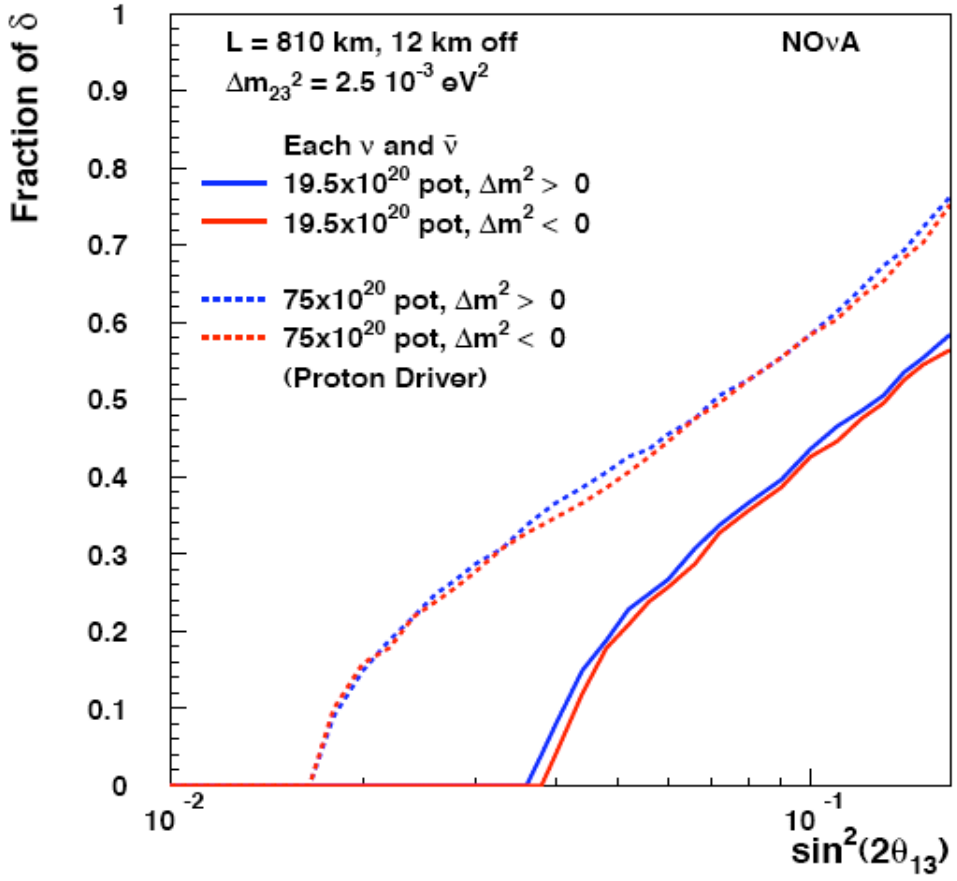


Resolution of the θ_{23} ambiguity

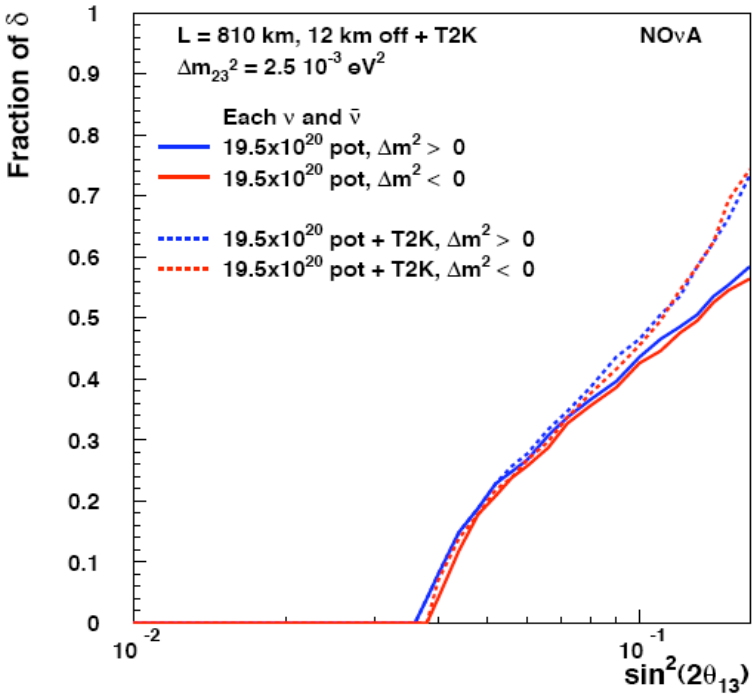


(There is some sensitivity to the mass ordering and δ. The blue line represents an average over these parameters.)

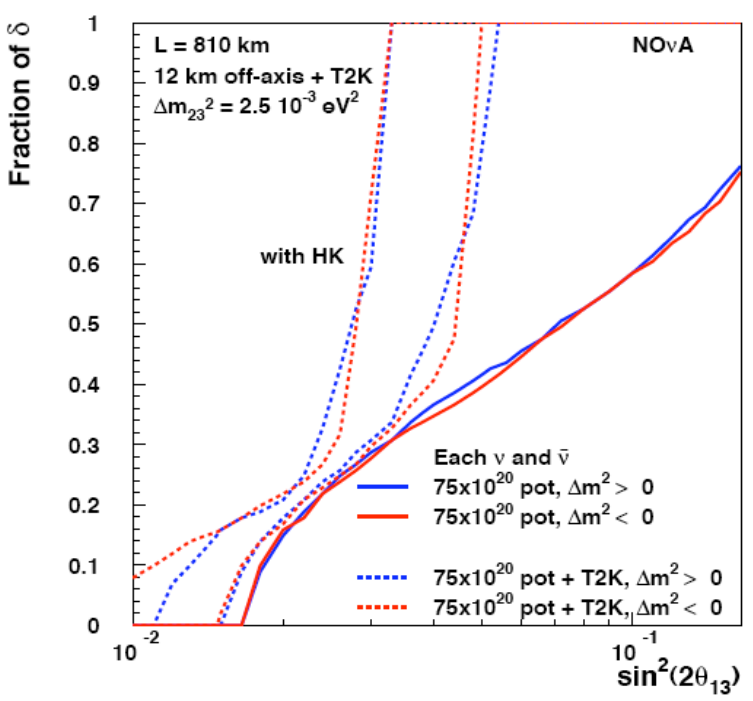
δ reach


Fraction of δ
L = 810 km, 12 km off
NOνA
Δm23² = 2.5 10⁻³ eV²
Each ν and ν̄
19.5x10²⁰ pot, Δm² > 0
19.5x10²⁰ pot, Δm² < 0
75x10²⁰ pot, Δm² > 0
75x10²⁰ pot, Δm² < 0
(Proton Driver)
sin²(2θ13)

NOvA + T2K
(to be updated)



NOνA with T2K Phase 1

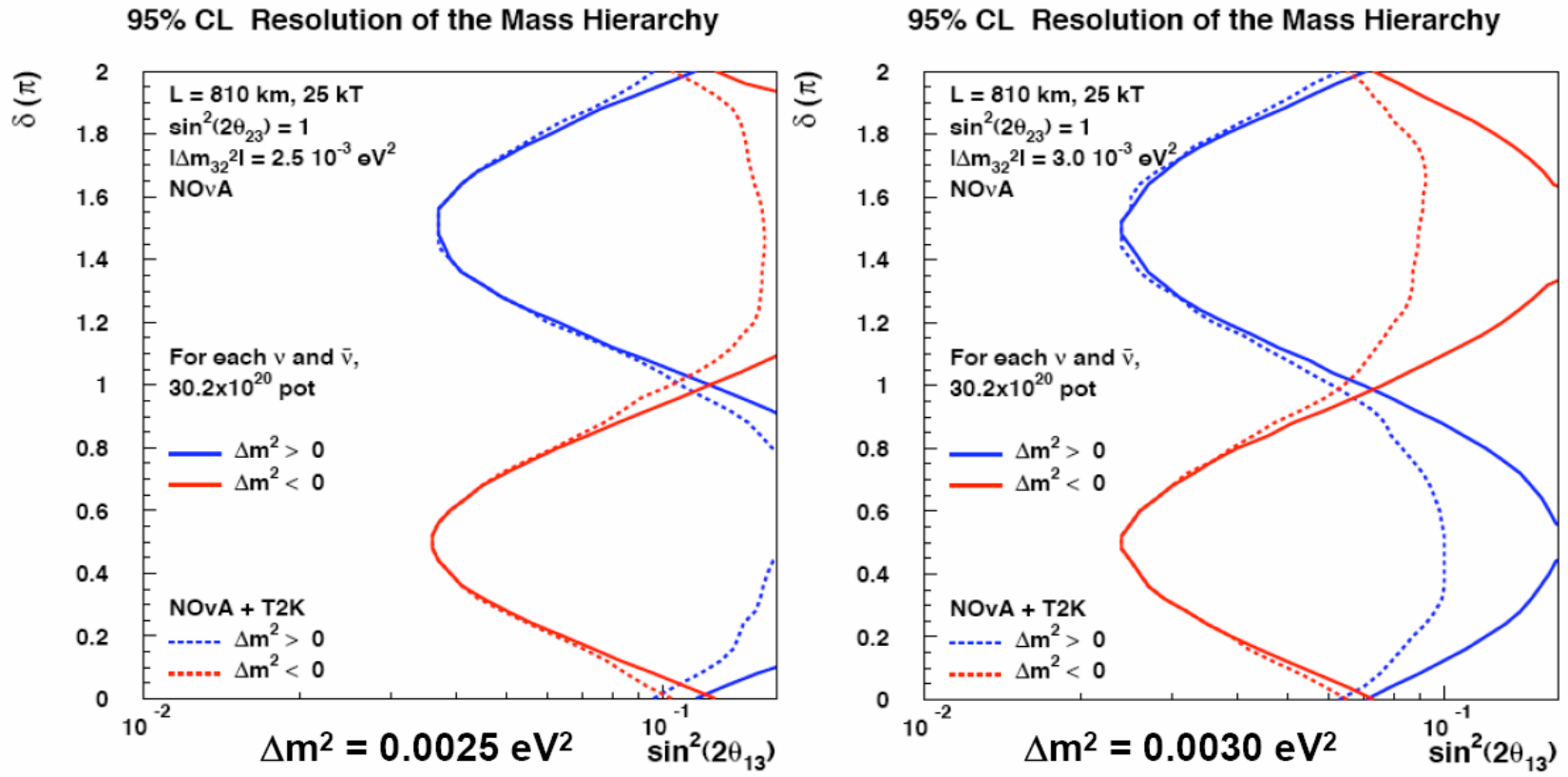


NOνA/PD with T2K Phase 2

95% CL Resolution of the Mass Ordering

Resolution of the mass hierarchy (with T2K)

- To be updated



NOvA ANU possible Timeline

- 2008 shutdown: GPP Civil Work started for penetrations and overall GPP work completed in January 2009
- Fall 2009 TeV shutdown starts (assume)
  - Most likely accelerator installation not ready to start until Spring 2010 (low level of funding in FY08 delays completion of ANU work required before this shutdown)
  - To complete accelerator upgrades, need ~6-8 month shutdown
- Fall 2010: Start up and commission recycler with protons (400kW)
- 1 year of running with NuMI LE target for MINERvA
- Fall 2011 shutdown: complete NuMI Target Hall work for 700kW power and change to ME neutrino beam configuration
- January 2012: Start up and commission recycler (700kW)
- During 2011: NOvA 5kT detector ready